VOLUME 104 PART A NUMBER 16 AUGUST 1957

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

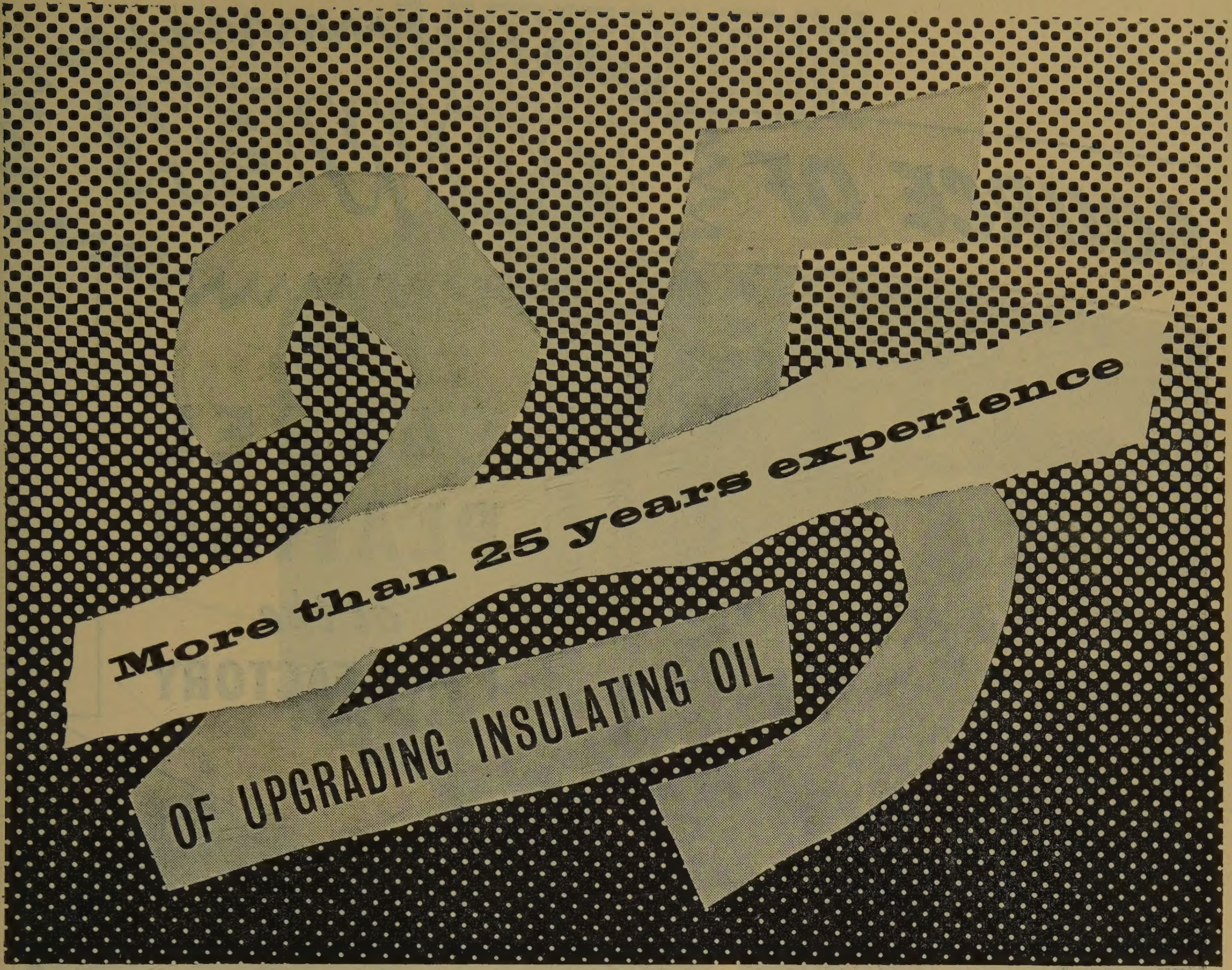
FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

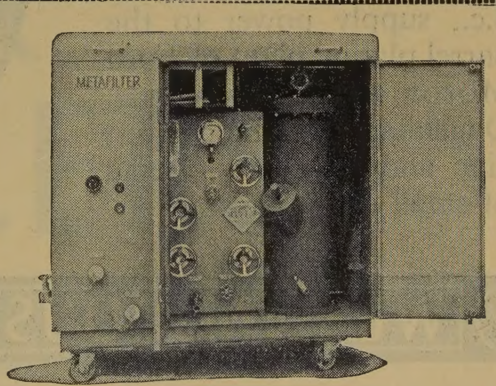
SAVOY PLACE · LONDON W.C.2

Price Ten Shillings



For more than a quarter of a century Metafilters have been accepted by electrical engineers for the COLD upgrading of switch and transformer oils. The filtration principle (using Metasil A.W.) is precisely the same as that employed for the removal of bacteria in other applications, thus ensuring absolute removal of solid impurities however finely divided, together with dehydration without recourse to heating and/or vacuum.

Electrical and consulting engineers, well-known oil companies, generating and distributing organisations, manufacturers of transformers and switchgear have chosen the Metafilter because (a) COLD filtration effects removal of impurities otherwise soluble in hot oil, (b) high di-electric strength and (c) no costly expenditure on replacement papers or sheets.



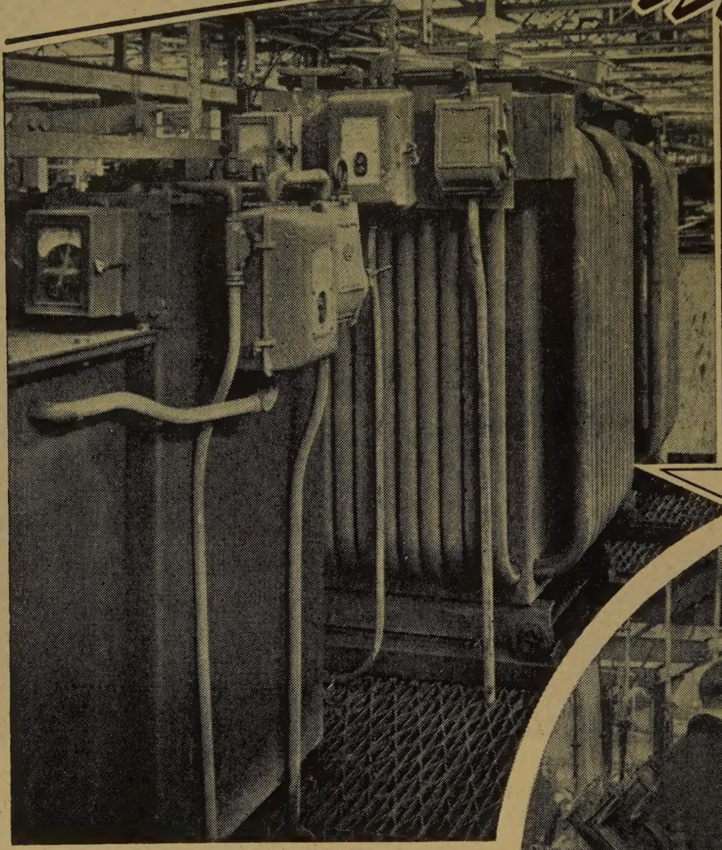
Metafilters for transformer and switch oils are available as static, portable and fully mobile units with capacities from 50 g.p.h. to 1000 g.p.h. Our experience and advice is at your disposal. Please write for Section 7 Catalogue giving details of our latest units.

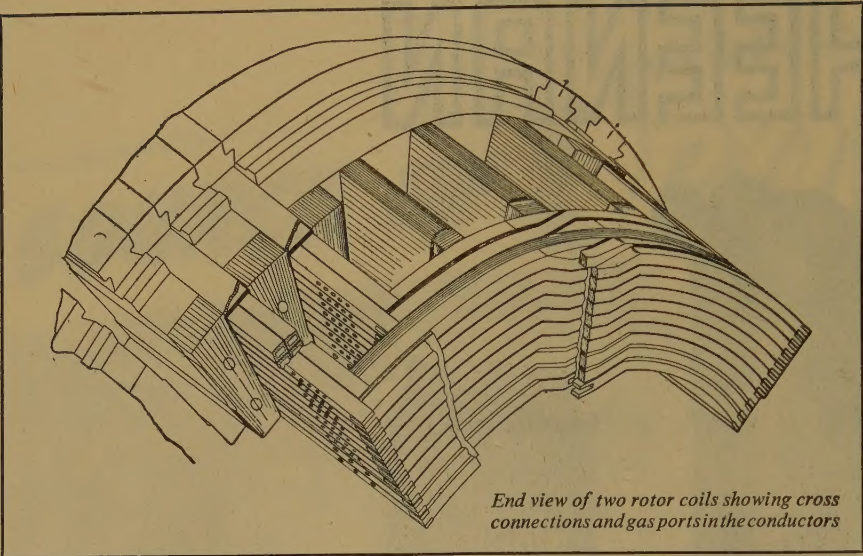
Metafilter

TRADE MARK

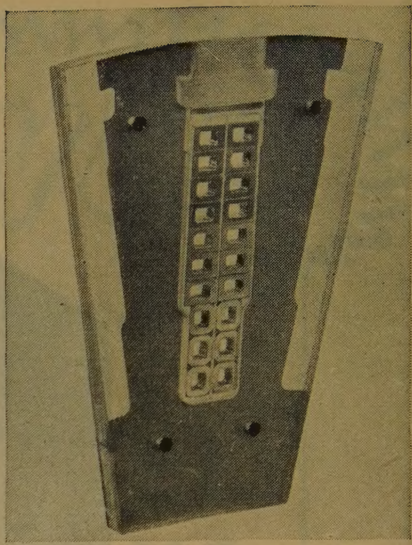
'PURITY WITH SIMPLICITY'

THE METAFILTRATION CO. LTD.
BELGRAVE RD., HOUNSLOW, MIDDX.
Phone: HOUnslow 1121-3





End view of two rotor coils showing cross connections and gas ports in the conductors



Arrangement of conductors and insulation in the slot.

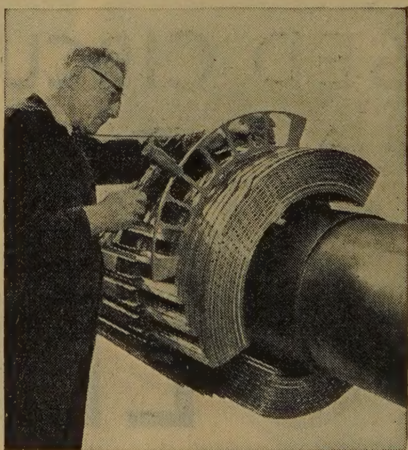
G.E.C.

Direct Cooling of Large Turbo-alternators

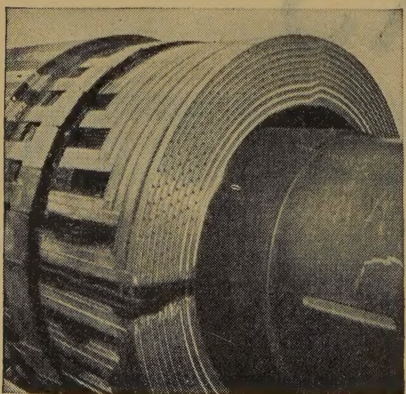
The output of large alternators driven by steam turbines is limited to a large extent by the amount of heat it is possible to dissipate from the rotor windings to keep them within permissible working temperatures.

By using direct cooling of the windings with hydrogen forced through hollow conductors, far greater outputs can be obtained from a given size of machine. The General Electric Company has standardised on this form of cooling for all turbo-alternators of 60 MW output and upwards.

The G.E.C. windings are fabricated from straight rectangular tubes and pre-formed end-connectors. Hydrogen is drawn through the conductors from one end of the rotor to the other in a cooling circuit which is independent of that for the stator.



Fitting segmental intercoil packing.



Completed winding

The G.E.C. practice has many important advantages:

(a) *Entry and outlet gas ports are in the side walls of the tubes outside the rotor body and clear of any insulation so that gas flow cannot be restricted by any relative movement of the copper and insulation.*

(b) *It permits the use of continuous slot insulation with normal creeping surfaces.*

(c) *Hot gases cannot escape from the rotor to the stator so that the temperature rise of the stator is unaffected by losses in the rotor windings.*

(d) *Gas flow through the separate conductors is equalised, thereby ensuring uniform temperature rises.*

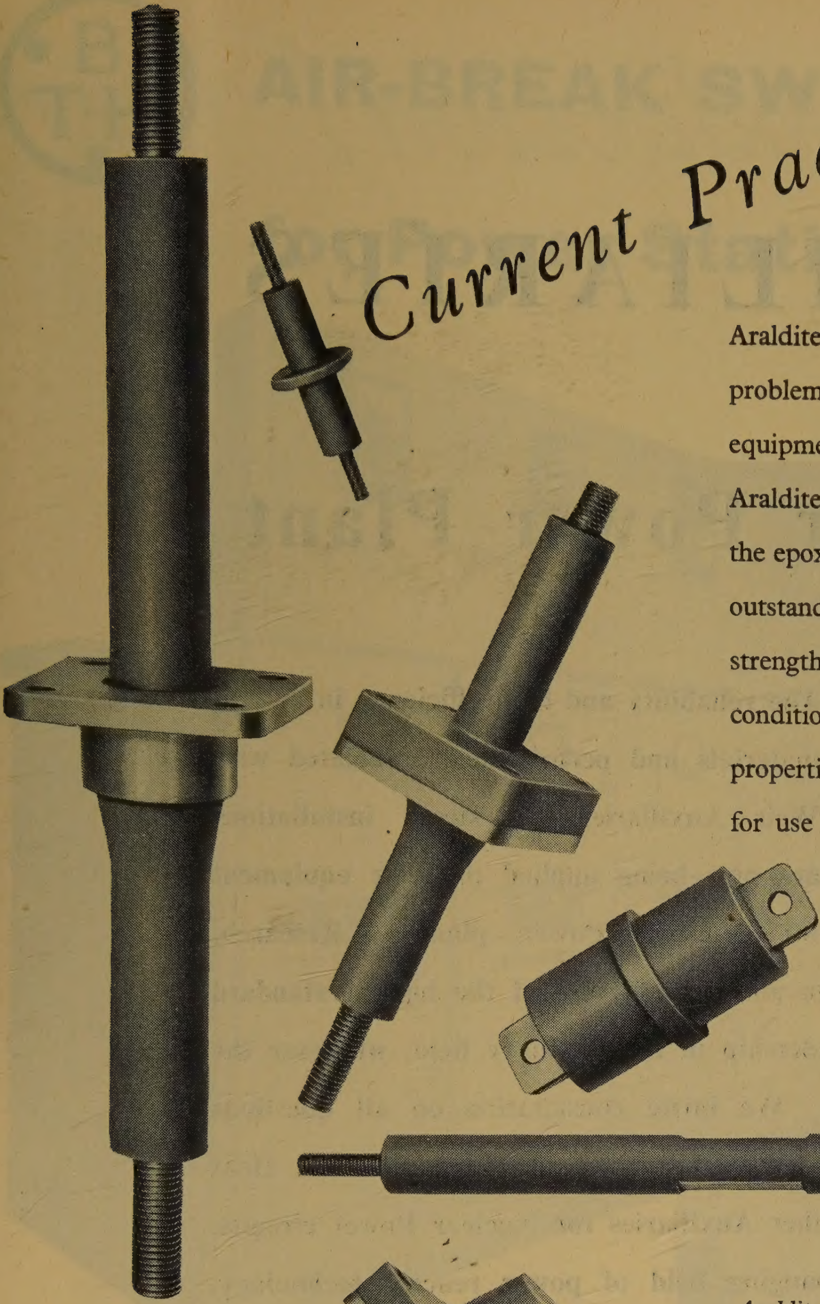
(e) *The slot profile and side-by-side arrangement of the conductors enable a normal number of turns to be accommodated without detriment to efficient gas flow or an under increase in excitation current.*

The advent of the direct-cooled turbo-alternator has revolutionised preconceived ideas of machine design, and has led to a material increase in output. Obviously factors other than the rotor temperature rise now determine the size of machine. By raising the limiting values of these factors G.E.C. have paved the way to further increases in output.

G.E.C. units embodying direct-cooling, with outputs of 60 MW and 120 MW are now being built for the Central Electricity Authority.

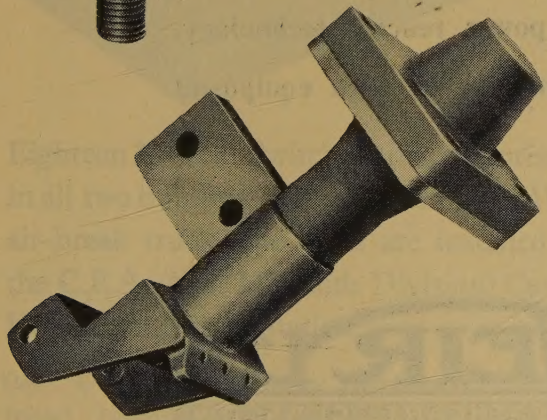
G.E.C.

THE GENERAL ELECTRIC COMPANY LTD.
MAGNET HOUSE, KINGSWAY, LONDON, W.C.2.



Current Practice

Araldite epoxy resins provide the answer to many problems encountered in the manufacture of electrical equipment. Bushings are a good example. Made with Araldite, they exploit the outstanding properties of the epoxies—remarkable void-free adhesion to metal, outstanding anti-tracking qualities, high mechanical strength, low shrinkage, stability, resistance to climatic conditions and chemicals and excellent dielectric properties. The components shown are cast bushings for use in air, oil or compound on potentials up to 11,000 V, and are manufactured by J. R. Ferguson (Electrical Engineers) Limited, Dukinfield, Cheshire.



Araldite epoxy resins are used

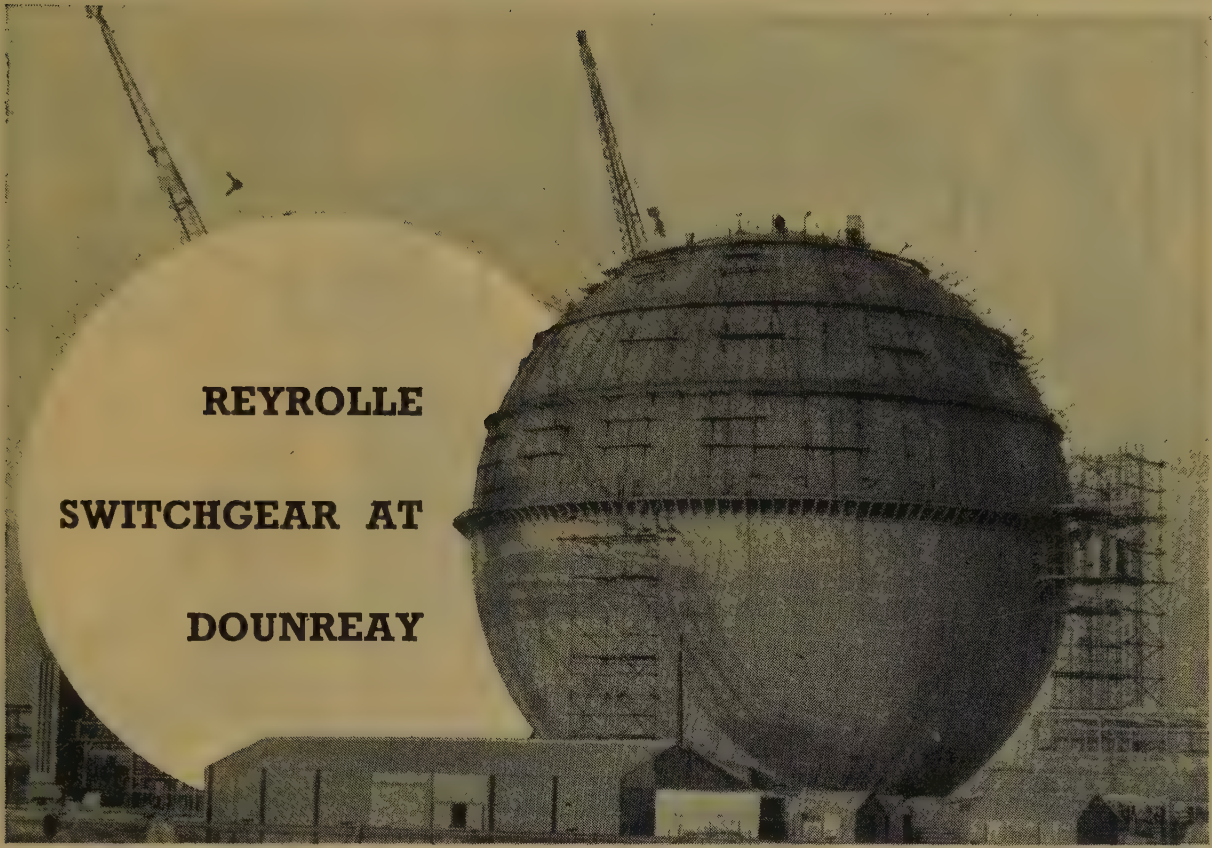
- ★ **for bonding metals, porcelain, glass, etc.**
- ★ **for casting high grade solid electrical insulation**
- ★ **for impregnating, potting or sealing electrical windings and components**
- ★ **for producing glass fibre laminates**
- ★ **for producing patterns, models, jigs and tools**
- ★ **as fillers for sheet metal work**
- ★ **as protective coatings for metals, wood and ceramic surfaces**

Araldite *epoxy resins*

Araldite is a registered trade name

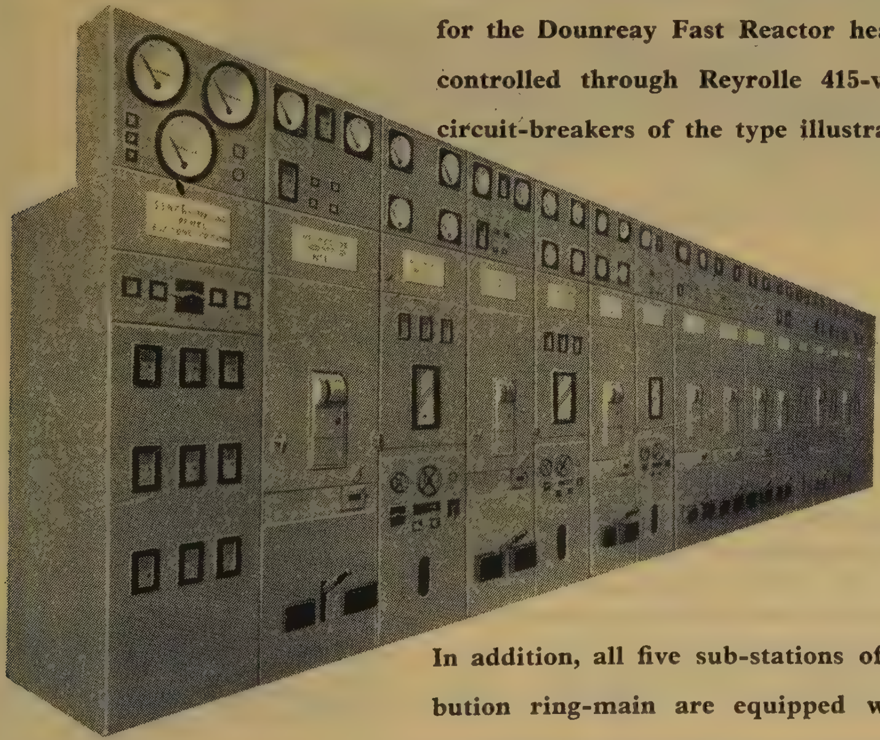
Aero Research Limited *A Ciba Company · Duxford, Cambridge · Tel: Sawston 2121*

AP317



Photograph by courtesy of the U.K.A.E.A

The electro-magnetic liquid-metal pumps and other services for the Dounreay Fast Reactor heat-exchanger system are controlled through Reyrolle 415-volt 31·5-MVA air-break circuit-breakers of the type illustrated.



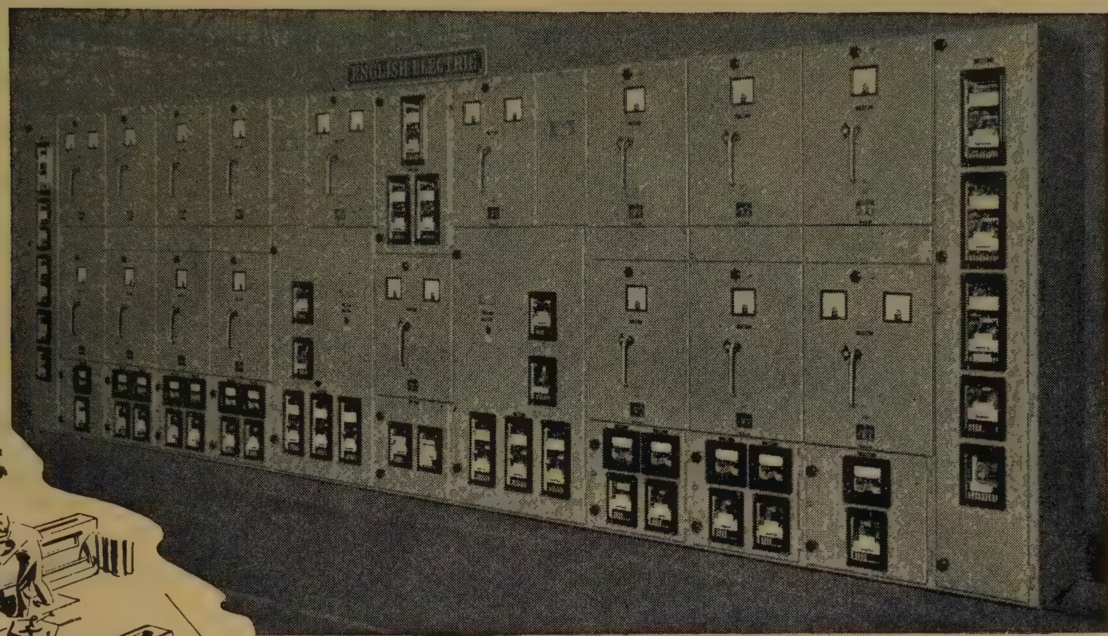
17-panel switchboard comprising Reyrolle type-S22A air-break circuit-breakers with associated control cubicles.

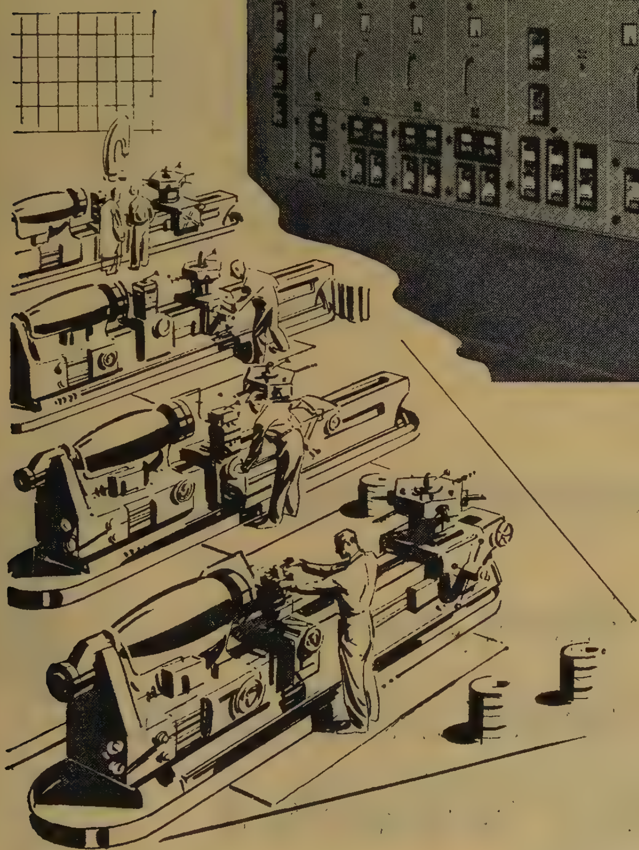
In addition, all five sub-stations of the main 11-kV distribution ring-main are equipped with Reyrolle metalclad switchboards with 350-MVA horizontal draw-out oil-break circuit-breakers.

Reyrolle

A. Reyrolle & Co. Ltd · Hebburn · County Durham · England

Electrical distribution for the up-to-date factory





'ENGLISH ELECTRIC' medium voltage air circuit-breakers, eminently suitable for the control of factory electrical distribution systems are installed in industrial concerns throughout the world.

The switchboard illustrated comprises 'ENGLISH ELECTRIC' 600 amp 15 MVA type OB2 air circuit-breakers for service up to 660 volts.

'ENGLISH ELECTRIC'

switchgear

THE ENGLISH ELECTRIC COMPANY LIMITED, MARCONI HOUSE, STRAND, LONDON, W.C.2

Switchgear Department, Liverpool

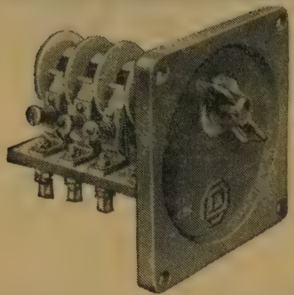
WORKS: STAFFORD • PRESTON • RUGBY • BRADFORD • LIVERPOOL • ACCRINGTON

SGL.2215

A SELECTION FROM

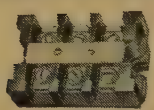
Miniature plunger, door interlock switch with N.O. contacts, 2-amps. 550-volts A.C. Size $2\frac{1}{8}''$ long × 1″ dia. (Type C.32 L 310).

A LARGE RANGE OF



Flush-mounting T.P. Isolating Switch for building-in Machine Tools, etc. 30-amp. 550-volts (Type C 95).

CONTROL ACCESSORIES



Terminal blocks (Type J 96) with clamp type terminals, white marker strip. Generous clearances between phases and to earth.
Made in the following sizes: 15-amp. 550-volt. 3-, 4- and 6-way. 30-amp. 550-volt 3- and 4-way.

The New Small A.C. Power Relay

Available 2-, 4- or 8-poles (with one or two coil circuit change-over contacts), fine silver double-break main contacts rated at 10-amps. 550-volts, Any pole can be N.O. or N.C.

Illustrated is a 4-pole enclosed relay

DONOVAN

THE DONOVAN ELECTRICAL CO. LTD.
Granville Street Birmingham I.
LONDON DEPOT: 149-151 YORK WAY, N.7. GLASGOW DEPOT: 22 PITT ST., C.2

Sales Engineers available in London, Birmingham, Manchester, Glasgow, Belfast, Bournemouth

---

UNIT TYPE "Y" INDUSTRIAL SWITCHGEAR

(METALCLAD)

FOR INDOOR OR OUTDOOR SERVICE ANYWHERE

Indoor totally enclosed unit construction type "Y" switchboard with incoming duplicate busbars feeding common outgoing circuits by means of interlocked fused switches of both 300 amp and 500 amp capacity. Duplicate busbars are directly connected at the rear to the incoming supply. Current Transformers are mounted in each outgoing chamber, and outgoing cables are from the back.

Supplied to Courtaulds Ltd.

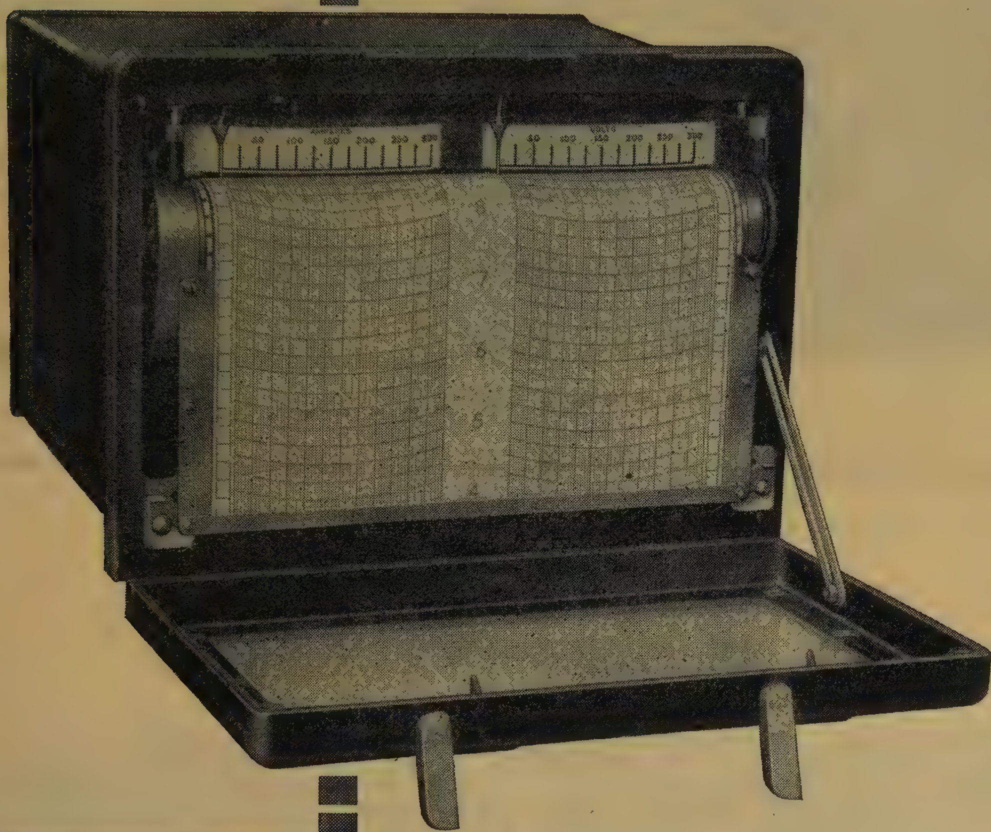
ELECTRO MECHANICAL MFG. CO. LTD.

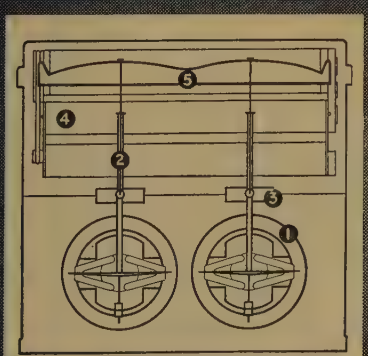
Head Office and Works: Marlborough St. SCARBOROUGH
London Office and Showroom: 133-135 Grand Buildings, Trafalgar Square, LONDON W.C.2
Associated with Yorkshire Switchgear and Eng. Co. Ltd.

RECORD

DUPLEX

GRAPHIC RECORDING INSTRUMENTS





Built to the same high standards and with the same outstanding performance as the single Graphic Recorder. Note the extremely compact space-saving layout.

1. Movements—high sensitivity, quick response.
2. Pen arms and Pens—capillary action.
3. Ink Troughs—almost unspillable.
4. Chart Mechanism—withdrawable for changing charts.
5. Scaleplate and Carrier.

Send for further details.

THE RECORD ELECTRICAL CO. LTD.

"CIRSCALE WORKS," BROADHEATH, ALTRINCHAM, CHESHIRE

C8917-1

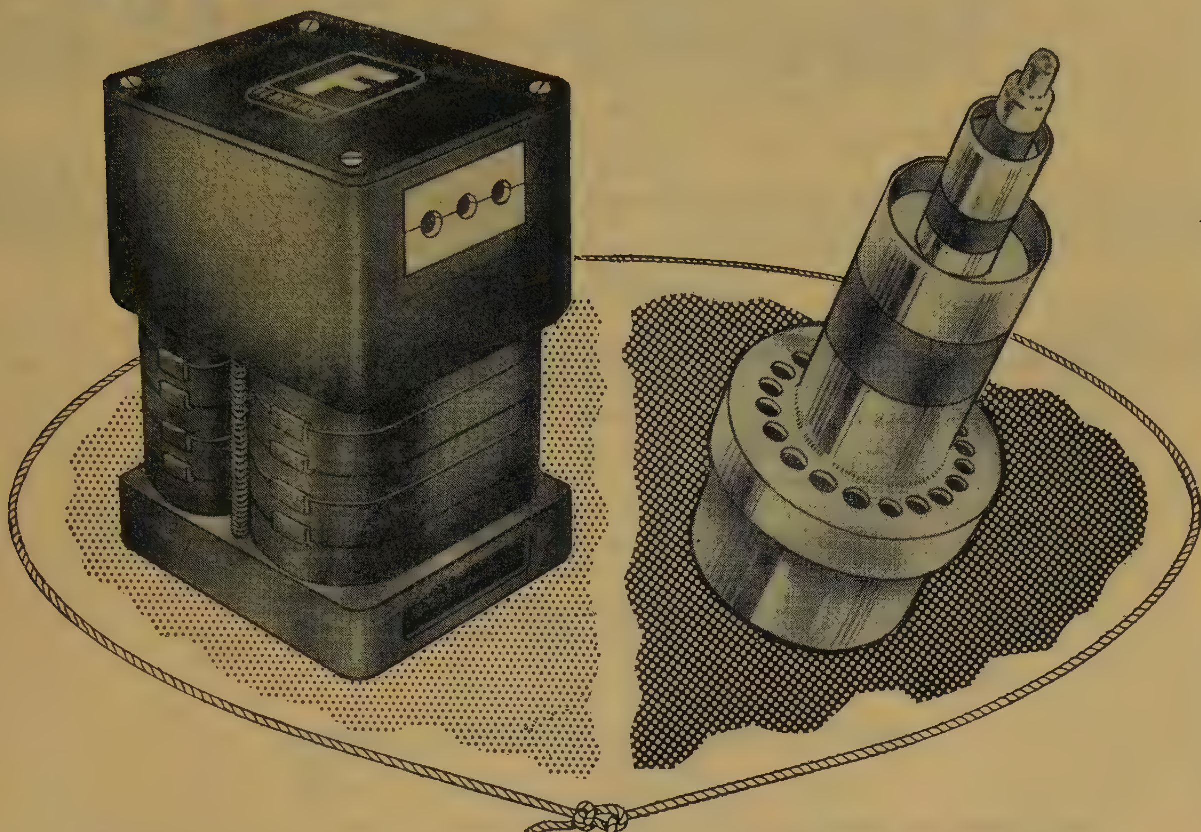
THE PROCEEDINGS OF THE
INSTITUTION OF ELECTRICAL ENGINEERS

TEN YEAR INDEX
1942—1951

A TEN-YEAR INDEX to the *Journal of The Institution of Electrical Engineers* for the years 1942–48 and the *Proceedings* 1949–51 (vol. 89–98) can be obtained on application to the Secretary.

The published price is £1 5s. 0d. (post free), but any member of The Institution may have a copy at the reduced price of £1 (post free).

~~bigger~~ smaller and better!



"Hitemp" Transformers

- Operational temperatures up to 250°C.
- Suitable for high altitude operation.
- Saving in size and weight.

Originally designed for supersonic aircraft, the "Hitemp" range of transformers has many applications throughout the electrical field.

Ceramic Valves

- High permissible temperature of operation.
- Ruggedised construction.
- Reduced dimensions.

The Ferranti range of Ceramic Valves includes power rectifiers, stabiliser triodes and R.F. power oscillators and amplifiers.

FERRANTI

FERRANTI LTD., FERRY ROAD, EDINBURGH • Tel: Granton 89181

ES/T36

INDEX OF ADVERTISERS

TRANSISTOR NEWS

from Mullard

OC70 and OC71 new high performance

Maximum working collector voltage tripled . . . . . maximum junction temperature raised to 75°C . . . . maximum power output correspondingly increased. These features characterise the increased performance of the new versions of the OC70 and OC71 junction transistors—increases which are made possible by further improvements in transistor production techniques backed by Mullard experience in the manufacture of many hundreds of thousands of transistors.

The new OC70 and OC71 are offered for use at collector voltages of 30V peak and 20V d.c. in both grounded base and grounded emitter where the circuit base resistance to earth is less than 500 ohms.

The increased maximum junction temperature now allowed may be exploited by circuit designers either in operating the OC70 and OC71 at the original power dissipations at 20°C higher ambient temperatures or in increasing the power dissipation at the original temperature. Some low power circuits can now be developed to work at the high *ambient* temperature of 70°C.

A revised data sheet including a curve showing the maximum d.c. collector voltage against external base-emitter circuit resistance is available from the address below.

ABRIDGED DATA *

Max. junction Temperature	75°C
Junction temp. rise above ambient in free air	0.4°C/mW
Max. collector dissipation at 45°C	75mW
Max collector dissipation at 25°C	125mW
Max. collector voltage, grounded base or grounded emitter:	
$V_{c\,(pk)}$ max.	–30V
V_c max.	–20V

*
Common characteristics for OC70 and OC71 general purpose and audio pre-amplifier transistors.

MULLARD LIMITED, COMMUNICATIONS AND INDUSTRIAL VALVE DEPARTMENT

Mullard

MULLARD HOUSE
TORRINGTON PLACE, LONDON, W.C.1

MV324b

THE PROCEEDINGS OF
THE INSTITUTION OF ELECTRICAL ENGINEERS

EDITED UNDER THE SUPERINTENDENCE OF W. K. BRASHER, C.B.E., M.A., M.I.E.E., SECRETARY

VOL. 104. PART A. No. 16. AUGUST 1957

621.311.25

Paper No. 2363
Aug. 1957

DEVELOPMENT OF GAS-COOLED REACTORS FOR POWER PRODUCTION

By R. V. MOORE, G.C., B.Sc.(Eng.), M.I.Mech.E., Member.

(*The paper was presented to the* BRITISH NUCLEAR ENERGY CONFERENCE *and was read in* LONDON *at a* SYMPOSIUM ON THE CALDER WORKS NUCLEAR POWER PLANT, 22*nd November*, 1956.)

SUMMARY

The paper reviews the possible development of gas-cooled graphite-moderated reactors for power production. It is shown that larger reactors of the Calder Hall type will produce electric power at a competitive cost in the United Kingdom.

A very promising line of development is towards higher-temperature operation, since this increases both the heat rating of the reactor and the overall efficiency of the plant, although it requires the development of new materials, particularly for cladding the uranium. As higher temperatures are reached, interest is stimulated in the oxide and carbide forms of uranium, and for very high temperatures an all-ceramic reactor core has been suggested.

The paper describes the use of recycled plutonium as a fuel, showing that under certain circumstances this is possible with a natural-uranium fuel. Comparison is also made of the relative merits of a number of possible coolant gases.

It is concluded that, given research and development effort, the gas-cooled graphite-moderated reactor is capable of considerable development. For the base-load application, cheaper power should be possible, and the range of application may be extended to smaller power units tailored for specific purposes.

LIST OF SYMBOLS

A = Capital cost of the complete station, £.
U = Cost of uranium fuel elements per tonne, £.
Q = Heat rate of the reactor(s), MW.
η = Overall efficiency = Electrical output/Q.
L = Load factor.
m = Average uranium fuel rating, MW/tonne.
D = Irradiation dosage of the fuel, MWD/tonne (= total heat energy released per tonne).
q = Heat output of most highly rated uranium channel.
d_P = Internal diameter of pressure vessel, ft.
p_s = Pitch of uranium channels, in.
α = Radial form factor of neutron flux, mean/maximum.
ϕ = Ratio between pumping power and q.
Q_E = Net electrical output, MW.

(1) INTRODUCTION

The target for the design study of the plant which eventually became the Calder works was a nuclear power station for base-load operation, using natural uranium fuel. The Calder works was a minor variation of this theme, in that emphasis was laid, in the design, on plutonium production. This was achieved without digression from the original purpose, and the plant is, in fact, a prototype from which nuclear power stations of continually improving performance will undoubtedly be developed. The purpose of the paper is to examine some of these possibilities.

(2) ANALYSIS OF THE COST OF ELECTRICITY PRODUCTION

If the Calder plant were run as a power station, and no value were attributed to the residual plutonium, it would produce electricity at about 1d. per kilowatt-hour. This would not be competitive with coal-fired stations in the United Kingdom, and so this cost must be reduced in future plant. It is therefore pertinent to analyse the factors which contribute to the cost of generation and establish how this vital reduction may be achieved.

As with conventional plants, the cost per kilowatt-hour may be taken as the sum of the capital charge, the fuel charge and the cost of operation and maintenance.

If it is assumed that interest and redemption on capital is charged at 4% per annum and that the plant has an economic life of 20 years, then:

(*a*) *Capital charge*

$$= \frac{2A}{Q\eta} \times \frac{1}{L} \times 10^{-6} \text{ penny per kWh (s.o.)} \quad . \quad . \quad (1)$$

(*b*) Since Q/m tonnes of uranium is always locked up in the reactor(s), there is an associated interest charge on the capital involved.

Fuel inventory charge

$$= \frac{1 \cdot 1U}{m\eta} \times \frac{1}{L} \times 10^{-6} \text{ penny per kWh (s.o.)} \quad . \quad (2)$$

Here U is the cost of the uranium fuel elements delivered to the power station and is considered to include an overhead component for fuel in the 'pipeline'.

(*c*) As the reactor operates, uranium is consumed.

Mr. Moore is with the United Kingdom Atomic Energy Authority (Industrial Group Headquarters).

The paper was published in the *Journal of the British Nuclear Energy Conference*, 1957, 2, p. 220.

Fuel consumption charge

$$= \frac{U}{D\eta} \times 10^{-2} \text{ penny per kWh (s.o.)} \quad . \quad . \quad . \quad (3)$$

This assumes that the uranium is passed once through the reactor; the possibilities of fuel recycling are considered later in the paper. No value is attributed to the residual plutonium.

The total cost per kilowatt-hour sent out is the sum of eqns. (1), (2) and (3) together with the unit charge for operation and maintenance.

Table 1 shows the composition of the cost per kilowatt-hour from the Calder works if the plant were operated at 80% load

Table 1

COST PER KILOWATT-HOUR

Cost component	Cost	
	d	%
Capital charge . .	0·56	53
Fuel inventory charge	0·10	9
Fuel consumption charge	0·35	33
Operation and maintenance . .	0·05	5
Total . .	1·06	100

factor as a nuclear power station and the fuel irradiated to an average value of 3000 MWD/tonne, it being assumed that the fuel elements cost £20000 per tonne. In considering the effect of the variables in eqns. (1)–(3) in reducing the cost per kilowatt-hour, these figures may be used to give a rough 'weighting' factor.

As with all power-producing plants, a high load factor leads to a reduction in the capital-charge component of the cost. With a nuclear plant of the type under consideration, an additional component—the fuel inventory charge—is similarly affected. These plants, passing through a phase of high capital cost, are therefore suitable as base-load units, which in the United Kingdom accords appropriately with the necessity to generate as much power as possible from resources other than coal. To operate at a high load factor implies a high order of plant availability, and the design of future nuclear power stations will no doubt incorporate improvements on the Calder works in this respect, e.g. charging and discharging uranium while the plant is operating at power.

Other than L, the variables in eqns. (1)–(3) may be arbitrarily classified into two categories, namely 'commercial factors', which are dependent on the market values of materials, equipment and labour, and 'design factors', which depend on design skill and the fundamental scientific and technical knowledge on which the design must be based.

Considering the capital charge, which constitutes about 50% of the kilowatt-hour cost (see Table 1), the term $A/Q\eta$ in eqn. (1) is the capital cost per megawatt sent out for the plant. This contains both 'commercial' and 'design' factors. The cost of the station depends mostly on the cost of materials and labour, but also to some extent on economical design. $Q\eta$, on the other hand, is entirely a design factor, the capital charge decreasing as the electricity output increases for a given capital investment. The ways in which this may be brought about are considered in later Sections.

The fuel inventory charge constitutes a small percentage of the cost per kilowatt-hour (<10%) and is composed of a commercial factor—the cost of uranium—and design factors m and η.

The fuel consumption charge (about 35% of the unit charge for $D = 3000$ MWD/tonne) is dependent on the 'commercial' factor U and 'design' factors η and D. The only factor to which

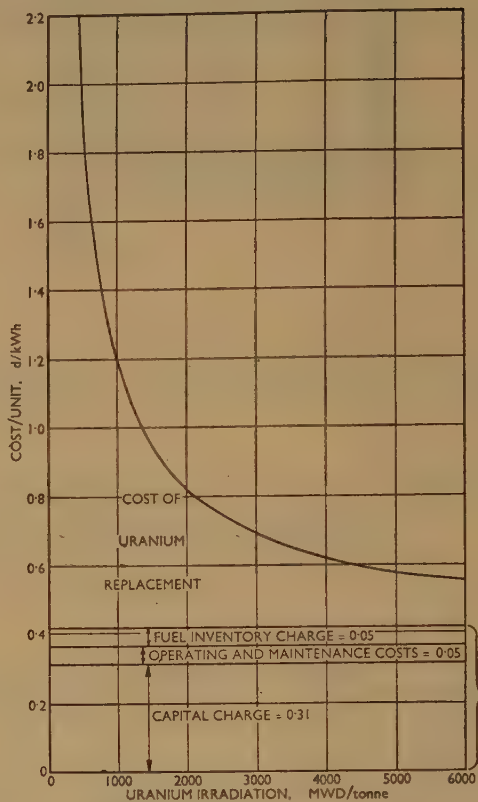


Fig. 1.—Cost per kilowatt-hour.

the whole kilowatt-hour cost is proportional (in the inverse ratio) is the overall efficiency, η, and small improvements are therefore important. Fig. 1 shows the cost per kilowatt-hour sent out from a nuclear power station costing £125 per kilowatt, operating at 80% load factor and 25% efficiency, as a function of the total amount of heat removed from each tonne of uranium costing £20000 per tonne, assuming the fuel elements have no residual value. The importance of being able to irradiate the fuel for as long as possible is obvious; particularly striking is the way in which the cost per kilowatt-hour falls rapidly up to about 2000 MWD/tonne.

The ability of a natural-uranium charge to achieve a long irradiation depends mainly on two factors: first, the neutron balance, necessary for the chain reaction, must be maintained; and secondly, the fuel elements must withstand the effects of irradiation damage under the operating conditions, without an excessive number of failures. As the uranium 235 content of the charge is consumed, it is replaced to some extent by plutonium formed from uranium 238 by neutron capture, and a small fraction of the plutonium so formed is itself fissioned. Recent experimental results from the Calder plant tend to confirm that 3000 MWD/tonne is obtainable before poisons accumulate in the fuel elements to the extent of inhibiting the chain reaction. The metallurgical limits on the life of the fuel elements arise from the tendency of uranium to increase in volume when irradiated at temperatures approaching the α/β change point of 660° C. Knowledge of the extent of this increase is not at present complete, but there is mounting evidence that 3000 MWD/tonne is attainable. Indeed, it is likely that this limit and the operating temperature may be raised by the adoption of certain alloys of uranium stabilized in the γ-phase.

So far, in this analysis, no value has been assigned to the plutonium formed in the irradiated fuel elements. Ultimately its value will depend on its worth as a fissile material, a few possi-

bilities being mentioned later. Its *minimum* value will, of course, be its cost of production, i.e. the cost of irradiation in reactors and subsequent chemical separation on discharge. In the recent White Paper[1] it is proposed that a credit should be allowed in calculating the cost per kilowatt-hour from the first natural-uranium power reactors for the by-product plutonium. Keeping this credit small tends to minimize the prime cost of plutonium and ease its economic utilization in the future. Any under-evaluation now will benefit future users of this artificial fuel.

(3) DEVELOPMENTS FROM THE CALDER PLANT

The performance of the Calder plant was limited primarily by two design factors, namely

(*a*) The thickness of steel plate from which the reactor pressure vessel is constructed, which determines the pressure of the carbon dioxide and the size of the reactor.
(*b*) The maximum temperature of the system.

The diameter of the reacting core was chosen so that the plant would operate at full power using natural-uranium fuel, with a small excess reactivity for satisfactory control. This consideration, in conjunction with the selection of steel plate 2 in thick for construction of the cylindrical pressure vessel, fixed the operating pressure of the carbon-dioxide system at 100 lb/in^2 gauge. The maximum temperature of the system was set by the temperature below which the uranium fuel elements would operate reliably, which was judged to be 400° C at the surface of the hottest fuel elements. The economic performance of this type of plant improves as these limits are raised.

(4) EFFECT OF INCREASING THE PLATE THICKNESS OF THE REACTOR VESSEL

Visualize a graphite core, with the uranium channels located on a square lattice, surrounded by a graphite reflector 3 ft thick within a cylindrical pressure vessel, with 1 ft radial clearance between the inside of the pressure vessel and the graphite; it can be shown that

$$Q = \frac{0{\cdot}113(d_p - 8)^2 q\alpha}{p_s^2} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The diameter of the reacting core of the Calder reactors is chosen so that the reactor is just supercritical at full power. Therefore a core of similar design and nuclear properties, but of greater diameter, will have excess reactivity above that required for operation of the plant. This can be profitably exploited by introducing absorbing material into the core in such a way that the neutron-flux curve is flattened and α is raised. Thus, increasing the pressure-vessel diameter, d_P, produces marked increases in Q, not only because of the increased number of channels, but also because of increases in α.

It is interesting to note from eqn. (4) the importance of maximizing q. In practice this must be done in relation to ϕ and the temperature-rise[2] ratio, r. The effectiveness of the extended surfaces for heat transfer from the fuel elements to the coolant is important in this facet of reactor design. It can also be seen from eqn. (4) that Q is increased as the lattice pitch, p_s, is decreased, but this has repercussions on the nuclear and mechanical design. Squeezing the lattice can be exercised profitably only over a limited range.

Before relating Q to the design of the reactor vessel, it is necessary to assess the effect of the absolute pressure of the circulating gas. Increasing the gas pressure reduces the fraction of the reactor heat rate required for the gas circulation according to an inverse square law. Increasing the pressure therefore brings diminishing returns. The final selection of the best value must be related to the optimization of a specific design of plant. In considering limited extrapolations from the Calder design, however, it is sufficient to consider an increase of, say, 25–50%. Taking values of gas pressure in this range and assuming a cylindrical pressure vessel, it is possible to evaluate eqn. (4) to give values of Q following increases in reactor-vessel plate thickness.

Typical results are plotted in Fig. 2 for gas pressures of 100, 125 and 150 lb/in^2 gauge, taking values of q and p_s from the Calder design of core, for constant values of ϕ. The marked

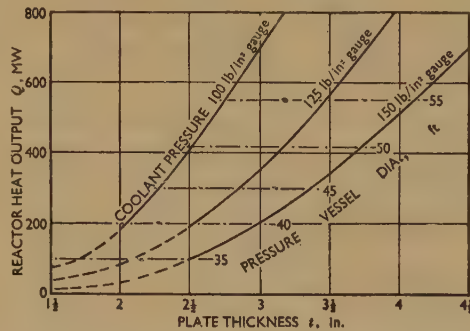


Fig. 2.—Variation of reactor heat output with pressure-vessel plate thickness for constant values of ϕ, with q and p_s as for the Calder plant.

effect of increasing the thickness of the pressure-vessel wall on the heat rate of the reactor can be clearly seen. For 3 in-thick plate, for example, the heat rate of the reactor could be 400–500 MW. It is obvious that the capital cost of the plant would increase proportionately much less than this increase in heat rate, and so the capital cost per kilowatt could be expected to drop considerably from the figure for the Calder plant.[3]

The above is a somewhat over-simplified approach to assessing the effect of increasing the size of the reactor. For example, there are several alternatives to a simple cylindrical pressure vessel fabricated in mild steel. But, in general, it can be concluded that increases in size, accompanied by limited increases in gas pressure, materially reduce the cost per kilowatt, without the need for further scientific or technical developments. This has immediate importance, for it means that nuclear power stations can be built of improved performance whose reliability is underwritten by the operating experience of the Calder works.

(5) EFFECT OF INCREASING THE MAXIMUM TEMPERATURE OF THE SYSTEM

Development in the direction of higher-temperature operation is particularly interesting. With regard to eqns. (1)–(3), increasing the maximum fuel-element temperature increases advantageously the values of Q, η and m. The question remains whether the effect of these improvements would be offset by unwanted changes of other factors, e.g. increases in U. The answer is complicated.

For service in a reactor, the uranium is clad with a metal of low neutron cross-section, to prevent escape of the radioactive fission products into the closed primary coolant circuit and to prevent any chemical reaction between the uranium and the coolant. The main possibilities are shown in Table 2. Stainless steel (18/8/1) has been included, although its neutron cross-section is relatively much higher than the other possibilities.

This Table shows that it is impossible to raise the maximum temperature of fuel elements, clad in either magnesium or aluminium, much above the 400° C adopted for the Calder plant, owing to the low melting point of these cladding materials. Note also that the alternative materials have thermal conductivities considerably worse than either aluminium or mag-

Table 2

POSSIBLE URANIUM CLADDING MATERIALS

Material	Neutron cross-section	Melting point	Thermal conductivity at 20° C	Density at 20° C
	cm^{-1}	deg C	C.H.U./h-ft-deg C	
Aluminium ..	0·0118	660	130	2·7
Magnesium ..	0·0023	650	90	1·74
Beryllium ..	0·00011	1284	70	1·85
Niobium ..	0·061	2415	36·4	8·57
Zirconium ..	0·0076	1850	14·4	6·5
Stainless steel.. (18/8/1)	0·227	1500	9·2	7·9

nesium. This, coupled with the increased heat-flux associated with the desired higher rating of the fuel, means that the fin efficiency of any extended surfaces, from fuel elements clad with one of the higher-melting-point metals, would fall so low that the fins would decrease markedly in efficacy.

The alternative is to increase the primary surface for heat transfer by spreading the uranium. This has repercussions on the nuclear design, since maximum reactivity is obtained with a fuel-element shape like a solid rod, which has a small surface/mass ratio. Raising the temperature of the fuel elements by a substantial margin from 400° C, therefore, implies a discontinuity of the present design. Not only must high-temperature fuel elements clad in little-known metals be developed, but a change in shape is involved which probably necessitates the use of enriched fuel.

It is pertinent to make a rough assessment of the effects of increased temperature. Let a fuel and single-channel geometry be assumed—say, a uranium configuration increasing the surface/mass ratio by a factor of 3 over the solid-rod case, and a channel 20 ft long through which carbon dioxide is pumped at 150 lb/in^2 gauge. Furthermore, assume that the gas enters the channel at 200° C and that ϕ is 2%. Fig. 3 shows the variation

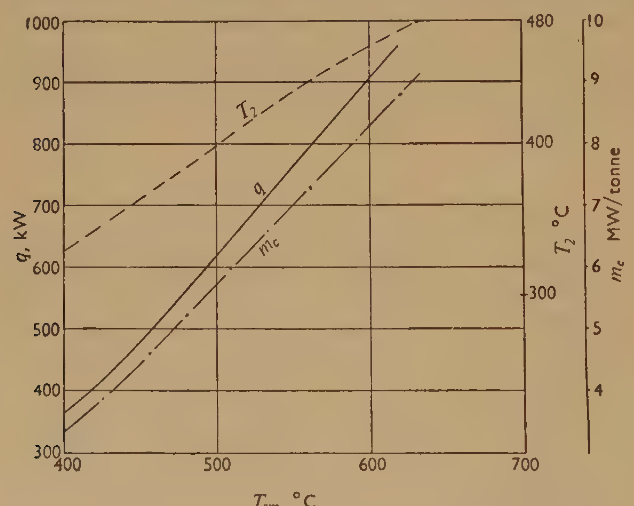


Fig. 3.—Variation of q, T_2 and m_c with T_{sm}, for a given value of ϕ.

of the channel heat-rate, q, the channel gas-outlet temperature, T_2, and the average rating of the uranium, m_c, in the most highly rated channel, against the maximum surface temperature of the fuel, T_{sm}.

The beneficial effects of increased fuel-element temperature on the performance of the reactor are at once apparent. The rising values of T_2 from the reactor enable the overall efficiency of the plant to be raised. T_2 is higher in the less highly rated channels of the reactor, so that the mixed or bulk gas-outlet temperature is somewhat higher than the values of T_2 plotted in Fig. 3. Making some assumptions which are typical of this type of plant, Fig. 4 shows the variation of overall efficiency with the

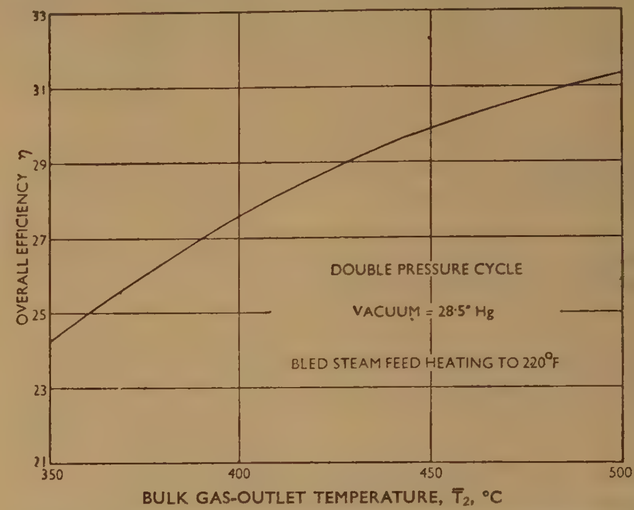


Fig. 4.—Variation of overall efficiency with bulk gas-outlet temperature.

bulk gas-outlet temperature, $\bar{T}_2$. Raising the maximum fuel-element temperature therefore increases the rating of the reactor and the overall efficiency of the plant.

For plants first using high-temperature fuel elements, the question arises of how far the maximum fuel-element temperature can be raised. This is a critical question for the designer to answer, for it involves a compromise between the best possible performance and the required degree of reliability in operation. In finality, the limits can be established satisfactorily only from experience of running plants.

Using data from Figs. 3 and 4 and evaluating eqn. (4) with appropriate value of p_s, Table 3 compares an extrapolated

Table 3

COMPARISON OF EXTRAPOLATED CALDER DESIGN (CASE A) AND PLANT WITH MAXIMUM FUEL-ELEMENT SURFACE TEMPERATURE OF 600° C (CASE B)

	Q	η	m	Q_E
	MW	%	MW/tonne	MW
Case A: Larger Calder design	400	25	2	100
Case B: High-temperature reactor				
(i) Flattened	1400	31	5·8	433
(ii) Unflattened	1100	31	4·5	340

Calder design, having a reacting core 40 ft in diameter, with a plant having a core of the same size but a maximum fuel-element surface temperature of 600° C—a value little better than a guess.

The increase in output and rating would substantially reduce the capital cost per kilowatt of the plant, but as explained above, the uranium would probably require enrichment, which would increase the fuel cost. In this respect the possibility of recycling plutonium is relevant; this is discussed later.

The heat rates from the reactors in cases B (i) and (ii) are rather large from a single unit, and in a specific design it might be

beneficial in optimization to decrease the core diameter, raise the gas pressure of the system and use larger temperature differences in the heat exchangers. This would reduce the size and cost of the external carbon-dioxide circuit, including the heat exchangers, and produce a more balanced design, which would be reflected in a favourable cost per kilowatt for the plant, even if the net output were reduced.

The development of gas-cooled reactors has been focused in the United Kingdom so far on the base-load application. The substantial increase in fuel rating obtained by high-temperature operation increases the economic feasibility of plants of lower power output and for lower load factor, using slightly enriched fuel.

The difficulties associated with the development of a high-temperature plant should not be underestimated. The basic compatibility problems are again thrown into sharp relief. Reactions between carbon dioxide and uranium, graphite, steel and canning-materials all enter a more active phase. The successful development of fuel elements (using a cladding metal on which experience is limited) to withstand the damage of long irradiation at high temperature requires extended application of very substantial resources.

Since this paper considers developments in gas-cooled reactors, possibility (*a*) is examined in more detail.

(6.1) Fuel Recycling

In a thermal reactor fuelled with uranium, uranium 235 is fissioned and some of the uranium 238 is converted by neutron capture into plutonium 239, which is fissile to thermal neutrons. By neutron capture, higher isotopes of plutonium are also formed and constitute an important fraction of the plutonium. On a 'once through' system in which the charge is irradiated up to, say, 3 000 MWD/tonne, only a small proportion of the plutonium is burnt and the discharged fuel elements contain plutonium, depleted uranium and fission products. In chemical separation plants, similar to the full-scale plants which the U.K.A.E.A. have now been operating for some years, the constituent parts can be separated. The possibility therefore arises of returning the plutonium and part of the depleted uranium to the fuel-element fabrication factory, there to be reconstituted with new feed uranium into fuel elements for charging into the reactor. Fig. 5 illustrates this fuel cycle.

If the plutonium is recycled, eventually an equilibrium condition is reached in which the rate of burning plutonium is

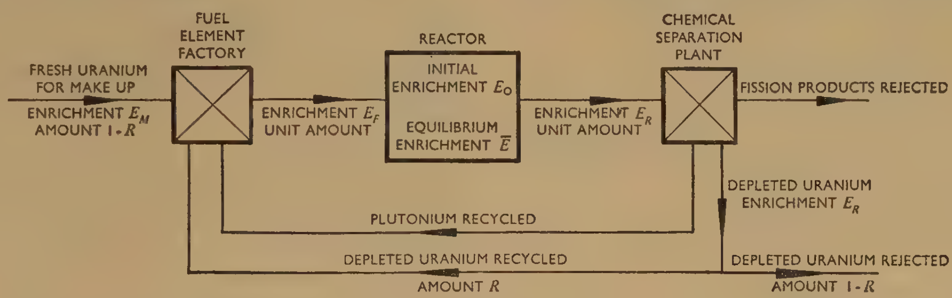


Fig. 5.—Fuel recycling.

(6) FUEL ECONOMY

So far, the basic type of reactor considered has been one operating on natural uranium on a 'once through' system. On the basis of the White Paper[1] it is apparent that by 1963–64 onwards, by-product plutonium will be produced in substantial quantities. According to the economy attained by the first plants, the cost of the plutonium, when separated from the irradiated fuel, will be less than the cost of producing uranium enriched in uranium 235 by the diffusion-plant process.

Apart from this possible economic incentive, there is a strong urge to use this fissile material, since by so doing conservation of nuclear fuels is improved. Inevitably the question arises of how by-product plutonium may most profitably be used, once supplies have been established. There appear to be at least four important possibilities, namely

(*a*) It could be used in new thermal reactors requiring initial enrichment, e.g. high-temperature gas-cooled reactors referred to in the preceding Section. The use of recycled plutonium in this way is the subject of a following Section.

(*b*) It could be used in fast-neutron breeder reactors operating on a plutonium-uranium 238 cycle and producing power. This leads to balanced fast and thermal reactor schemes in which a comparatively large fraction of the uranium 238 is used, arising from the fact that fast reactors breed more fissile material than they consume.[4] An experimental fast reactor is currently under construction at Dounreay, in the north of Scotland.

(*c*) It could be used in fast or thermal reactors as the fissile material for a plutonium-thorium 'transition cycle' producing power and uranium 233 as a by-product. The latter might subsequently be used in a self-sustaining uranium-233–thorium cycle in thermal reactors, if these prove practicable, or might be used as the fissile material in fast reactors, breeding from uranium 238 or thorium.

(*d*) It might be used in power plants requiring highly enriched fuel, e.g. plants designed with a large power/weight ratio.

balanced by the rate of production of fresh plutonium. This is possible in a reactor with a conversion factor of less than unity if the fissile material, short of the amount required for the reactor to operate, is made up from uranium 235 in new uranium fed into the system. The analysis of such a system is complicated by the fact that as the plutonium is taken to longer irradiations the higher isotopes influence to an increasing degree the performance of the reactor. By successive neutron capture plutonium 239 can become plutonium 241, 242 and 243. Plutonium 243 is radioactive with a short half-life (5 h) and effectively decays almost immediately on formation to americium 243, which would be removed in chemical processing after irradiation. Plutonium 240, 241 and 242 build up during the approach to the equilibrium system, when the rate of their formation is equal to their rate of destruction by natural decay or neutron capture. Plutonium 240 and 242 are *not* fissile isotopes, but plutonium 241 is fissile and produces neutrons during fission.

Table 4

NUMBER OF PLUTONIUM ATOMS REQUIRED TO REPLACE ONE URANIUM 235 ATOM WITHOUT ALTERING THE REACTIVITY

	Number of plutonium atoms
For pure plutonium 239 fuel	0·44
For 3 000 MWD/tonne plutonium from a natural-uranium reactor	0·75
For equilibrium plutonium	2·38
For equilibrium plutonium without plutonium 242	0·99

The effect of the higher isotopes of plutonium can be seen from Table 4, the values being typical of a reactor of the type shown in Case B of Table 3. The mean moderator temperature is assumed to be 427° C. The Table shows the number of plu-

tonium atoms required to replace one uranium 235 atom without altering the reactivity. The adverse effect of plutonium 242 in the system is clearly demonstrated by these figures.

There are a number of variations of the basic cycle;[5,6] in the paper some of the simpler relationships are defined and a numerical example is quoted for explanatory purposes. From Fig. 5 it can be seen that

$$E_F = E_M(1 - R) + RE_R \quad . \quad . \quad . \quad . \quad . \quad (5)$$

An important case occurs when $E_F < 1$, for here natural uranium make-up can be used, i.e. $E_M = 1$.

Now let

$$w = \frac{\text{Mean concentration of uranium 235 in reactor}}{\text{Initial concentration of uranium 235 in reactor}} = \frac{\bar{E}}{E_F} \quad . \quad (6)$$

Φ = Thermal neutron flux.
σ_{235} = Total absorption cross-section of uranium 235.
T = Fuel irradiation time.

Then

$$w = \frac{\int_0^T \varepsilon^{-\sigma_{235}\Phi t}dt}{T} = \frac{1 - \varepsilon^{-\sigma_{235}\Phi T}}{\sigma_{235}\Phi T}$$

$$= \frac{1 - h}{-\log_\varepsilon h} = \frac{\bar{E}}{E_F} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where $1 - h$ = Fraction of uranium 235 destroyed per cycle.

The equilibrium enrichment, $\bar{E}$, is dependent only on the reactor design and the nuclear constants and is independent of the actual recycling procedure. For a given reactor, $\bar{E}$ can be calculated; therefore eqn. (7) gives the relation between burn-up per cycle and the fraction of uranium 235 supplied from the feed material.

Having defined $(1 - h)$, it is apparent that

$$E_R = hE_f \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Eqn. (8) gives the relation between concentration of reject uranium and the concentration of the feed uranium for a given burn-up of uranium 235 per cycle. Lastly, combining eqns. (5), (6) and (8), we may write

$$R = \frac{E_M - \dfrac{\bar{E}}{w}}{E_M - hE_F} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

or, if $E_M = 1$,

$$R = \frac{1 - \dfrac{\bar{E}}{w}}{1 - hE_F} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Eqn. (10) gives the fraction of depleted uranium recycled for a reactor of given design in terms of burn-up per cycle and the uranium 235 content of the uranium feed, the make-up being natural uranium.

The effect of fuel recycling may be illustrated by specific example. Consider the reactor associated with Case B(ii), Table 3, operating on an equilibrium cycle, each successive charge being irradiated to 3 000 MWD/tonne. For this case:

$$\text{Initial enrichment} = 1{\cdot}16$$
$$\bar{E} = 0{\cdot}63$$
$$E_F = 0{\cdot}71$$
$$R = 0{\cdot}65$$
$$E_R = 0{\cdot}56$$

from which $(1 - R) = 0{\cdot}35$ and therefore each tonne of natural uranium make-up would produce 8 500 MWD of heat, or the utilization of uranium fuel resources would be improved over the once-through system by a factor of 3. The reactor design chosen in this example is not particularly well adapted to operate on fuel recycling, and this factor might conceivably be increased by a design more appropriate for this system of fueling. It is clear that potentially the important advantages of fuel recycling are:

(a) It could reduce the natural uranium requirement to meet a given power demand by a significant factor.
(b) Under certain conditions, applicable to gas-cooled graphite-moderated reactors, designs requiring initially a charge of slightly enriched uranium can be subsequently fed with natural uranium once equilibrium conditions are reached.

An economic assessment of fuel recycling at the present time cannot be made with any exactness. The effect of hold-up of fuel in processing, the relative quantities in the reactor and 'pipeline', and the effect of processing-rate/feed-rate are some of the factors involved. The cost of fabricating fuel elements with α-active plutonium is another important factor in determining the overall economy of fuel recycling. Note that if all the plutonium is recycled in the reactor in which it is produced, the net electricity cost does not depend, in the equilibrium state, on fixing a value of plutonium. In fact, a lower limit for the value of plutonium can be deduced from considering such a cycle, since it would be uneconomic to sell plutonium at such a low price that the net cost of electricity from the reactor which could use recycled plutonium instead of uranium 235 make-up was greater than if the plutonium were recycled.[5]

(7) COMPARISON OF VARIOUS GASES AS COOLANTS

For reactors so far discussed it has been assumed that the coolant gas is carbon dioxide. Investigation carried out during the 1951–53, design study showed that, in addition to this hydrogen, helium and nitrogen might be considered for cooling power reactors.

Coolants must be compared on a number of criteria—safety, cost, availability, purity, thermal and irradiation stability, chemical compatibility, neutron absorbing properties, the degree to which they become radioactive—all in addition to their heat-transfer properties. It is scarcely surprising that an ideal coolant does not exist.

In comparing the heat-transfer properties of gases, reference must be made to the type of heat-transfer surface. Two cases have been discussed in this paper, namely

(a) Where reliance is placed on primary heat-transfer surface.
(b) Where most of the heat is transferred from extended surfaces.

Case (a) is analysed by Diamond and Hall[7] under certain specified conditions and assuming Reynolds's analogy to apply. A criterion ($M^2c_p^3$) is developed for comparing gases used to remove the same amounts of heat from channels of the same length and area under the same temperature and pressure conditions. The ratio of heat removed to pumping power is proportional to $M^2c_p^3$. Values at 300° C for the four gases under consideration are shown in Table 5.

Table 5

VALUES OF $M^2c_p^3$

Gas	M^2c_p
Nitrogen (or air)	13·0
Helium	30·6
Carbon dioxide	31·4
Hydrogen	167·0

M = Molecular weight. c_p = Specific heat.

The ratio of pumping power to heat output for a given gas is proportional to the square of the heat output, so that by substituting, for example, hydrogen for carbon dioxide, an increase

in heat output by a factor of $\sqrt{(167/30 \cdot 65)}$, i.e. of $2 \cdot 33$, could apparently be obtained. However, with unchanged inlet and maximum fuel-element temperatures, a fall in gas outlet temperature would occur. Diamond and Hall point out also that the criterion is not completely satisfactory, because the heat-transfer area is a variable dependent on the gas properties, and unacceptable area might be needed to obtain a given performance.

The same criterion applies also to transverse fins of the type used in the Calder plant, for which Reynolds's analogy does *not* apply, but for which a fin-efficiency correlation can be made as shown in the paper by Fortescue and Hall.[8] Similar criteria could no doubt be developed for other types of extended surface. If a 'better' gas is substituted for the original one, and an attempt made to restore the ratio of pumping power to heat output, the outlet temperature from the reactor can be expected to fall seriously in all cases of extended surface, owing to the reduced efficiency of the extended surface.

The only satisfactory way of comparing the performance of different gases is to evaluate for a specific design. In general, when this is done the differences are not so marked as expressions like $M^2c_p^3$ suggest. Carbon dioxide was chosen for the Calder Hall reactors because it was the best compromise between all the requirements. As the temperature of reactor systems is raised, new conditions will be created and helium or nitrogen may supplant carbon dioxide, since comparatively, they are inert gases. Hydrogen is inert at ordinary temperatures, but is chemically active at elevated temperature, and is highly inflammable. Considerable research work would have to be carried out before its feasibility was established for cooling nuclear power reactors; however, its superior heat-transfer properties and favourable nuclear properties are a considerable incentive.

(8) NON-METALLIC FUEL ELEMENTS

As the temperature at which the fuel elements are designed to operate is raised, interest is stimulated in ceramic fuels, i.e. compounds of uranium, plutonium and thorium with oxygen and carbon. The properties of uranium, uranium carbide and uranium oxide are compared in Table 6.

Table 6

PROPERTIES OF URANIUM, URANIUM CARBIDE AND URANIUM OXIDE

Fuel	Melting point	Density	Thermal conductivity at 50° C,
	deg C		C.H.U./h-ft-deg C
U	1 133	19	16·7
UC	2 250	13·5	19·7
UO_2	2 800	11	5·0
UC_2	2 400	11·28	19·0

Compared with the metals, they have much higher melting points, are brittle, and soften only at comparatively high temperatures. Most ceramics have thermal conductivities much lower than those of metals, but this is not the case with the uranium carbides, which have values similar to that of the uranium metal.

Uranium oxide was used in the first reactor built in the United Kingdom (Gleep), but uranium metal was later preferred, since its density is higher—a favourable property from the nuclear point of view, and particularly important when natural uranium is used. As concentrated fissile materials become available, however, interest in the ceramic forms of uranium will probably return. Generally speaking, ceramics are more resistant to coolant attack than metals, and uranium oxide is inert to both carbon dioxide and hydrogen. Uranium oxide and uranium carbide are reasonably stable in air, although uranium dicarbide and thorium carbide are very reactive. In addition to their favourable high-temperature properties, there is some experimental evidence to indicate that their irradiation resistance is considerably better than that of the metal.

(9) VERY-HIGH-TEMPERATURE (V.H.T.) REACTORS

Ceramic fuels, and the fact that graphite itself is a refractory material, have led to the possibility of a very-high-temperature, gas-cooled reactor in which all metals are excluded from the core. This type of reactor has been given considerable impetus recently by Fortescue. As a type it might be developed to meet the requirements of groups (*a*) or (*d*) in Section 6.

Fuel rating is generally discussed in terms of heat removed from a given mass of uranium (megawatts per tonne), a small proportion only of which, in natural or slightly enriched uranium, is fissile material. This definition of rating carries with it a concept of the size of the plant; possibly some 20% of the capital cost of a plant is inversely proportional to this figure. The fuel inventory charge [see eqn. (2)] is also reduced as the rating is increased. Another way of expressing fuel rating is in terms of *fissile material*, a concept more important in relation to fuel cycles. With natural uranium the fissile-material rating is 140 times the uranium rating. Table 7 shows the uranium and fissile-material ratings for the reactors discussed in the paper.

Table 7

URANIUM AND FISSILE-MATERIAL RATINGS

Reactor	Uranium rating	Fissile-material rating
	MW/tonne	MW/kg
Calder Works	1·4	0·2
Case A of Table 3	2·0	0·3
Case B (i) of Table 3 . .	5·8	0·8
Possible v.h.t. reactor . .	—	1–2

With the v.h.t. reactor the possibility exists of virtually 'diluting' the fissile material with the moderator; in this case, high fissile-material ratings are possible (see Table 7) and at the same time good neutron economy is preserved.

At the high temperatures associated with this type of reactor (typically, a gas outlet temperature of 800° C) the problems associated with materials are acute. Attaining a high degree of thermal and irradiation stability of the graphite and the ceramic fuel at high temperature and high neutron flux presents a formidable research problem, as does preventing the spread of fission products into the primary cooling circuit. These ideally should be confined to the fuel, as with conventional fuel elements clad in metal. The incentive for development, however, is high. It is calculated that the overall efficiency of such plants could exceed 40%, while the high fuel rating would lead to a further reduction in the capital cost per kilowatt, when compared with high-temperature reactors with metallic cladding of the fuel elements, as typified in Case B(i) of Table 3.

(10) GAS-TURBINE CYCLES

The prospect of higher gas temperatures leads inevitably to the consideration of gas-turbine cycles. For plants of large

power output, a cycle of the same general type as developed by Escher–Wyss is applicable. Stenning and Howieson of Chalk River, Canada, have carried out preliminary calculations for this type of plant, the general scheme of which is shown in Fig. 6.

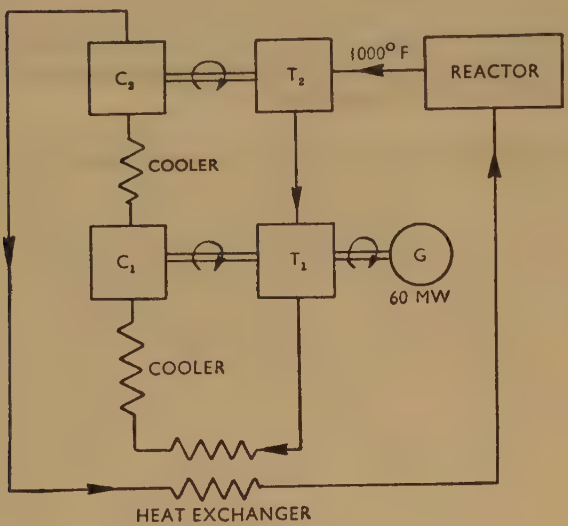


Fig. 6.—Gas-turbine cycle.

T_1 = L.P. turbine.
T_2 = H.P. turbine.
C_1 = L.P. compressor.
C_2 = H.P. compressor.
G = Generator.

The hot gas from the reactor feeds high- and low-pressure turbines, the latter driving the alternator. Two-stage compression with intercooling is used, the h.p. and l.p. compressors being driven by the h.p. and l.p. turbines respectively.

Comparing the merits of carbon dioxide and helium, Stenning and Howieson conclude that the rotating machinery for the carbon-dioxide cycle has approximately half the volume of that required for the helium plant, but the heat exchangers have nearly double the volume, which suggests that marginally the carbon-dioxide plant might be cheaper to build. In carrying out preliminary design calculations for a 60 MW (electrical) plant they assumed a gas pressure of 300 lb/in^2 absolute and a top gas temperature of 1 000° F. These conditions are particularly interesting, since they probably represent something near the minimum conditions for such a cycle, the machinery being large and costly yet possible to design and construct. Even at 1 000° F the calculated efficiency is 29%, and if the temperature were raised to 1 250° F this would increase to 38%. For the capital cost of the plant to be competitive with steam plants, however, it would appear that the system pressure would have to be considerably higher than 300 lb/in^2 gauge.

Potentially the gas-turbine cycle becomes worth while in conjunction with the v.h.t. type of reactor, but for the system shown in Fig. 6 to be feasible, fission products would have to be contained within the reactor.

(11) SUMMARY AND CONCLUSIONS

It must be remembered that the paper discusses the possible developments of one particular class of reactor—the gas-cooled graphite-moderated type—and therefore reviews the future on rather a narrow front. These plants, fuelled with natural uranium, however, are the spearhead of the United Kingdom's nuclear power programme. Incorporating many detail improvements, the first series basically will be larger versions of the Calder Hall plant.

The performance improves rapidly as the designed fuel-element temperature is raised, the capital cost per kilowatt is reduced through increased fuel rating, the kilowatt-hour cost being further decreased as the efficiency rises. The solid-rod fuel element, clad in magnesium or aluminium, is reaching the end of its possible development. A new range of reactors is opened up with the introduction of fuel elements with larger surface/mass ratios, and clad with a metal of high melting point. These reactors will probably need initial enrichment, although their design may well enable them to operate on recycled fuel with a natural uranium feed. The higher ratings possible with these designs may extend the field of application from base-load power plants to plants producing smaller amounts of power at a worth-while cost.

Still higher-temperature systems may be developed in which metals are excluded from the core, the fuel being ceramic and dispersed in the graphite moderator. Many severe problems are associated with this design, but successful development would lead to still cheaper power and to compact systems for which gas-turbine cycles would be economically feasible as an alternative to steam.

(12) ACKNOWLEDGMENTS

The author wishes to acknowledge the help of Mr. W. Bonsall and Mr. J. Waters with the calculations for the paper, and Mr. L. M. Wyatt for data on materials.

(13) REFERENCES

(1) 'A Programme of Nuclear Power', Cmd. 9389 (H.M. Stationery Office, London, 1955).
(2) Packman, G., and Cutts, B.: 'Basic Design of Reactor', *Journal of the British Nuclear Energy Conference*, 1957, **2**, p. 102.
(3) Moore, R. V., Haslam, R. J., Duffet, G., and Packman, G.: 'A 200 MW Nuclear Power Station', A.E.R.E. Report No. UK/C3/11, 1954.
(4) Rennie, C. A.: 'Economic Power from Fast Breeder Reactors', *Journal of Nuclear Energy*, 1954, **1**, p. 39.
(5) Dunworth, J. V.: 'Fuel Cycles and Types of Reactor', *Proceedings of the Internation Conference on the Peaceful Uses of Atomic Energy* (Geneva, 1955), P/403, 1956, **3**, p. 14.
(6) Mummery, P. W., and Syrett, J. J.: 'Fuel Recycling in Equilibrium Uranium-Plutonium Thermal Reactors', A.E.R.E. Report No. R/P1915, 1956.
(7) Diamond, J., and Hall, W. B.: 'Heat Removal from Nuclear-Power Reactors', *Journal of the British Nuclear Energy Conference*, 1956, **1**, p. 227.
(8) Fortescue, P., and Hall, W. B.: 'Heat-Transfer Experiments on the Fuel Elements', *ibid.*, 1957, **2**, p. 83.

621.314.2 : 621.3.014.3

Paper No. 2317 S
Feb. 1957

MECHANICAL STRENGTH OF POWER TRANSFORMERS IN SERVICE

By E. T. NORRIS, Member.

(*The paper was first received* 15*th September, and in revised form* 5*th December*, 1956. *It was published in February*, 1957, *and was read before the* SUPPLY SECTION 27*th February, the* NORTH-EASTERN CENTRE 11*th March, and the* NORTH-WESTERN SUPPLY GROUP 10*th April*, 1957.)

SUMMARY

The mechanical stresses in power transformers have steadily increased with transformer size and supply-system capacity. Short-circuit currents are generally based on the rupturing capacity of circuit-breakers which has increased in 25 years from 1 500 MVA to 25 000 MVA.

The position has been accentuated in recent years by the established practice of auto-reclosing, which makes repeated switching on to possible faults a normal practice, and the introduction of fault throwing for inter-tripping purposes, where dead short-circuits are deliberately created under normally controlled conditions.

Using only simple mathematics, it is shown that the mechanical strength of a transformer is not a simple single value as is implied in the short-circuit clauses of standard transformer specifications. Some of the strains are progressive, and some of the stresses cumulative, leading to short-term and long-term characteristics. The resulting categories of mechanical strength are defined as initial, critical and ultimate, the last named being usually the crucial one.

It is shown how the performance in service can be predetermined and the expectation of life, in terms of number of short-circuits, predicted for any given operating conditions.

Service records of failures on short-circuits are analysed and found to support the predicted values.

Methods of improving the expectation of life are considered.

LIST OF SYMBOLS

a = Net area of winding insulation support, in^2.
b = Percentage compression of electromagnetic centres per ton/in^2 stress.
c = Percentage compression of axial insulation per ton/in^2 stress.
C = Crushing strength of insulation and supports, ton/in^2.
d_0 = Percentage initial axial displacement of electromagnetic centres.
d = Percentage final axial displacement of electromagnetic centres.
f = Frequency, c/s.
K_i = Ideal short-circuit strength as a multiple of full-load rating.
K_0 = Initial short-circuit strength as a multiple of full-load rating.
K_c = Critical short-circuit strength as a multiple of full-load rating.
K_1 = Ultimate short-circuit strength due to axial stresses.
K_r = Ultimate short-circuit strength due to radial stresses.
K_s = Short-circuit stress in service.
l = Length of radial flux leakage path, in.
L = Axial length of winding, in.
n = Number of short-circuits.
p = Axial stress, tons/in^2 per 1% dissymmetry. Crest asymmetrical value at full load.
P = I^2R loss in winding, kW.
S = Rating, kilovolt-amperes per phase.
t_1 = Total conductor axial insulation thickness, per unit of L.
t_2 = Total winding spacer and washer insulation thickness, per unit of L.
t_3 = Total end insulation thickness, per unit of L.
w = Effective radial width of leakage flux path, in.
W = Width of core window, in.
x = Per-unit reactance.

Mr. Norris is a consulting engineer with Ferranti Ltd.

(1) INTRODUCTION

Many papers have been published during the last 40 years dealing with mechanical stresses in transformer windings. A pertinent selection of these is given in the Bibliography.

On the other hand, very little publicity or attention has been given to the mechanical performance of transformers in service. This is perhaps because this performance has been apparently good and reassuring. Failures due specifically to mechanical stresses are rare, though, of course, serious when they do occur. The position is actually not quite so satisfactory. Mechanical stresses are usually unsuspected, and their effects are often obscured by different and more serious stresses occurring after the initial failure. Moreover, the major forces are cumulative in effect,[4, 6] so that final failures will not necessarily be due to a severe fault but may be the culminating effect—in other words, the last straw. Notwithstanding these conditions, short-circuit stresses have frequently caused serious trouble in the past and seem likely to cause even more in the future.

It is proposed in the paper not to derive formulae for calculating forces and stresses, as this has been done extensively and in detail in published literature,[7–18] but to study the effect of these forces on the life and performance of transformers in service under normal and abnormal operating conditions.

(2) PRESENT POSITION

Apart from the experience described above, there is a general assumption that mechanical stresses are not alarming, because most national transformer specifications demand that the transformer shall satisfactorily withstand a short-circuit with full line voltage maintained, i.e. with infinite system capacity behind the transformer.[25, 26, 27]

It is believed that manufacturers have acquiesced in these requirements because (*a*) such severe conditions cannot arise in service, (*b*) a test compliance is not practicable, and (*c*) they do not know that their transformers would not meet the test. It is likely, therefore, that manufacturers have treated this guarantee as a risk that can be commercially accepted, whilst purchasers and users have assumed that it was a technical guarantee fully covered by an adequate factor of safety. This distinction has been discussed elsewhere.[28] The false sense of security thus engendered has recently been exposed by Stenkvist.[1] In an extensive search of published literature he could find only two records of short-circuit tests on large power transformers.[2, 3] An additional case is described in Reference 4, but none of the tests complies fully with the national specifications corresponding to full voltage being maintained on the transformer. To complete the picture, Reference 5 describes the only known case of a short-circuit test of full value, but here the transformer was only 1 200 kVA, which is hardly representative of modern large-transformer practice.

The subject, nevertheless, is of great importance as abnormal conditions may occur at any time. There is a continuous growth in system capacities. The rupturing power of circuit-breakers

has increased during the last 25 years from 1 500 MVA to 25 000 MVA, or more. The short-circuit current permitted by system-planning engineers is generally based on this value and has increased accordingly.

The universal practice of auto-reclosing makes deliberate and repeated switching on to possible faults a normal practice. The more recent development of fault throwing, in which phase-to-earth fault throwers are used for inter-tripping purposes, seems likely to grow. This involves deliberately creating a dead short-circuit under normally controlled conditions. Further, owing to the growth of system capacity, many transformers are now operating under short-circuit mechanical-stress conditions much more severe than those envisaged when they were designed. This trend is likely to continue into the future.

(3) FORCES AT WORK

The principal forces at work are radial and axial. In concentric-winding transformers radial forces involve adequate support of the inner winding whilst the outer winding relies upon the tensile strength of the conductor. For all but very large transformers these limits suffice, and radial stresses have not generally been regarded as serious. It has recently been suggested[1, 18] that the mechanical characteristics of the copper or aluminium conductor may be of vital importance, and this aspect is considered later.

Axial forces include an unavoidable compression of both windings and a displacement due to electromagnetic dissymmetry. This may be caused by any of the following:

(a) Tappings in the windings.
(b) Inaccuracy of assembly.
(c) Shrinkage of insulation due to impregnation and drying out.
(d) Compression of the insulation in service.
(e) The necessity for a whole number of turns in a coil.
(f) The necessity for a whole number of coils.
(g) Oil cooling ducts.
(h) Conductor transpositions.
(j) Insulation reinforcement and grading.
(k) The different voltage and current ratings of the two windings to be balanced.

If the windings are interleaved or sandwiched, as is usual in shell-type construction, instead of being concentric, the radial and axial forces become interchanged in the foregoing description.

(4) CALCULATION OF STRESSES

Since force calculations are used in the paper only for example and illustration and in order to simplify the development of performance in service—which is the main purpose of the paper—single concentric windings will be assumed consisting of helical coils or stacks of disc coils. This is the usual construction for core-type transformers.

This simplified study can easily be extended to any modern type of winding and arrangement of tappings, including multi-layer coils and multi-concentric windings, by using appropriate formulae published in technical literature[7–18] and, in particular, the E.R.A. Reports by Waters.[9, 11–14]

(5) DEFINITION OF MECHANICAL STRENGTH

The mechanical strength of a transformer is determined by heavy fault or short-circuit conditions and is expressed here as the ratio of the r.m.s. value of the symmetrical short-circuit current to the full-load rated current. Since the forces are dependent on the maximum instantaneous value of the current, the corresponding stresses are based on the crest value of the short-circuit current, assuming an asymmetry factor of 1·8, as defined in Appendix C of B.S. 116: 1952.

(6) RADIAL STRENGTH

Radial forces between windings exert a compression or inward force against the core on the inner winding and an outward force on the outer winding. The force in tons at full-load asymmetrical crest value is*

$$\frac{2\cdot 07}{w}\frac{S}{f}x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

(6.1) Compression Force

This force is resisted by compression of the conductor and by radial support from an insulating cylinder or from the core.[9, 18, 2] On the largest transformers the support is taken right back to the core, and it is possible to meet full short-circuit stresses even with multi-concentric windings as a practical proposition.

(6.2) Tensile Force

The outward radial force is usually taken by tensile stress in the conductor. The stress can be deduced from eqn. (1), but it can also be expressed[1] as the average† stress on the copper conductor in tons per square inch as

$$\frac{0\cdot 083P}{L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The stress/strain relation for high-conductivity annealed copper as used in transformer windings is non-linear,[1, 18, 21, 3] and Fig. 1 gives some typical values. Although all the curves

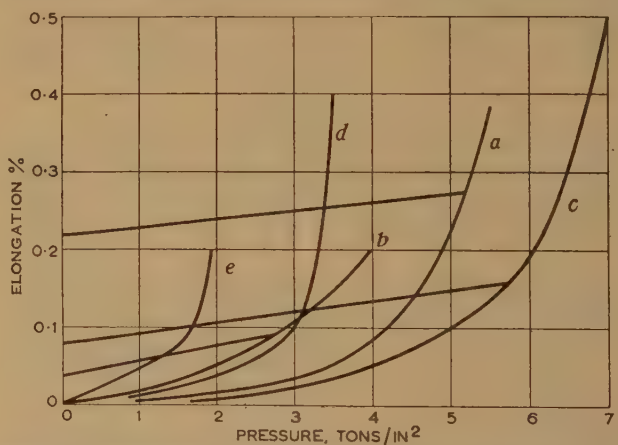


Fig. 1.—Stress/strain curves for high-conductivity annealed copper.

Curve (a) Reference 1.
Curve (b) Reference 21.
Curve (c) Reference 18.
Curve (d) Copper Development Association typical values.
Curve (e) Reference 30.

are for annealed copper, the spread of values is large and is due partly to the appreciable effect of minute impurities in the metal and partly to varying degrees of cold working in the course of handling. These variations will of course occur in practice. Curve (e) is for dead-soft annealed copper and may be taken as one extreme of the range. Curve (d), furnished by the Copper Development Association, is based on the average strain-hardening constants for 22 different curves determined by various authorities.

When the force is released there is a permanent extension, as

* All the formulae in the paper are for purposes of illustration and exposition. Formulae used in design practice, though more accurate, are more complicated and obscure in dimensions.

† The stress is actually not uniform in a radial direction but is greatest for the inner conductor and falls approximately linearly to zero for the outermost conductor. The resulting internal strain adjustments within the winding are complex,[18] but for the present purpose the average stress, as expressed in eqn. (2), may be assumed.

shown by the curves. Normally the extension would cause some work hardening and so increase the stress at which the copper would yield under subsequent forces. This is not likely to occur under short-circuit conditions as temperatures up to 250° C are possible. Moreover, copper will anneal with time at any temperature above the recrystallization temperature of about 100° C, depending upon its purity. Since this is a normal working temperature for the conductor and since there may be years between short-circuits, it must be assumed, to be on the safe side, that the conductor copper will always have to meet short-circuit stresses in the annealed condition as given in Fig. 1. For these reasons also there seems to be no advantage in winding with hard-drawn or semi-hard-drawn conductors, even if that were a practical possibility.

(6.2.1) Cumulative Effect of Short-Circuit Stresses.

After the first short-circuit the conductor is permanently stretched by a small amount. On the next short-circuit a similar addition will occur, since the forces will be virtually unchanged

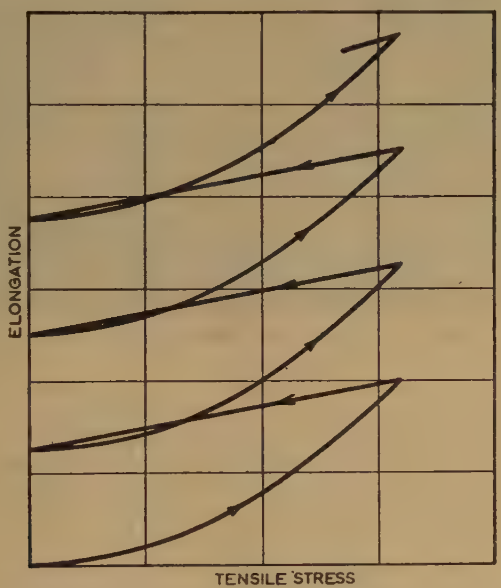


Fig. 2.—Progressive effect of radial short-circuit stresses.

and the conductor still in the same annealed condition. The effect is progressive, as illustrated in Fig. 2, the outer winding growing bigger in diameter for each short-circuit.

(6.2.2) Expectation of Life in Service.

It is difficult to say what the limit is for failure to occur, but, as a typical example, assume that a stress of 3·5 tons/in² causes a permanent elongation or strain of 0·3%. Five short-circuits will then give 1·5% elongation. For a large transformer with an outer-winding diameter of 50 in this gives an ultimate increase of 0·75 in. It is unlikely that a larger increase could be permitted.

From eqn. (2),

$$\frac{0 \cdot 083P}{L}K_r^2 = 3 \cdot 5$$

whence

$$K_r = 6 \cdot 50\sqrt{\frac{L}{P}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

It is suggested in Section 10 that five short-circuits are equivalent to roughly 45 nominal short-circuits in service.

Typical values of K_r for a number of large power transformers are given in Fig. 3. There is a natural tendency for K_r to fall with increasing capacity, as shown for the smaller ratings. This fall is arrested for the larger sizes because K_r depends upon the apparent power per h.t.-l.t. group, and this is often reduced by double or triple concentric windings, and in single-phase units by two or more wound legs per unit. This division is generally determined by the restriction in the maximum permissible reactance. For example, a 100 MVA single-phase unit may have exactly the same windings as a 50 MVA unit of the same voltage and ratio but with two legs wound instead of one. The value of K_r would then be the same for both sizes.

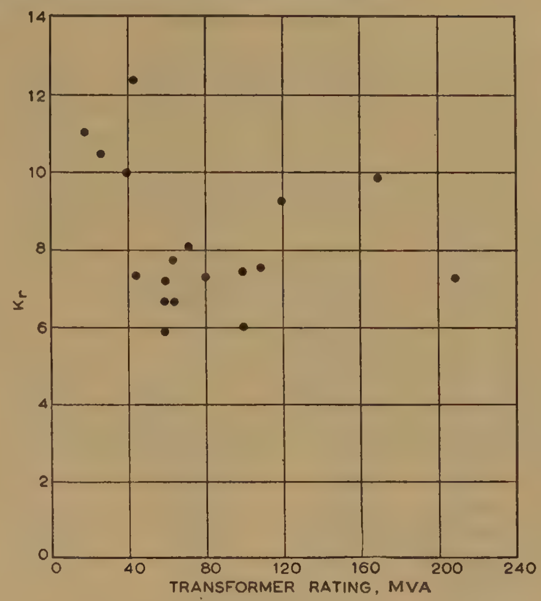


Fig. 3.—Typical values of radial short-circuit strength.

In cases where the strength K_r obtained in this manner is inadequate, additional mechanical restraint must be provided or an alloyed conductor such as silver-bearing copper employed.[31]

(7) AXIAL STRENGTH

(7.1) Compressive Force

The axial force normally considered[7–18] in published literature is a compressive force acting on both windings and giving maximum pressure in the middle of the leg. The total compressive force in tons on both windings is roughly

$$\frac{2}{L}\frac{S}{f}x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The division of this force between the two windings is complex, but the inner winding usually has the bigger share. Waters[12] suggests that, to be on the safe side, 100% should be allowed for the inner winding and 50% for the outer.

The normal method of dealing with this force is to clamp the windings[9, 16, 18] axially under a pressure not less than the maximum value of this force, so that short-circuits will merely result in lessening of the clamping pressure and not in loosening or compression of the windings. This principle would be good if the compressive force were the only axial force or even the most severe one. It will be shown later that this is not the case and for these additional forces such clamping pressure is harmful, in that it directly increases the stresses.[4]

In magnitude the compressive force is not, in general, serious enough to be a limitation in the mechanical strength of the transformer.

(7.2) Displacement Force

The displacement force is usually ignored in published literature. It is one of the main purposes of the paper to suggest that, on the contrary, it is the most serious and dangerous force to be considered and that it is responsible, somewhat insidiously, for most, if not all, failures in service due to mechanical stresses.

The force in question is a repulsive one between the two windings. In theory it is zero if the two windings are electromagnetically perfectly balanced. In practice it may apparently and initially be small and controllable, especially in the larger transformers where it is not seriously accentuated by tapping asymmetries. These factors may account for the general disregard of it in published literature. Moreover, even if the windings are perfectly balanced, and this can only be done theoretically on paper, the position is, alarmingly, one of unstable equilibrium, like an egg standing on end. In practice some initial dissymmetry is unavoidable. In one case where the electromagnetic balance was perfect in design the windings moved in opposite directions in two phases in a short-circuit test[3] of an 80 000 kVA transformer, owing to unavoidable small asymmetries in erection.

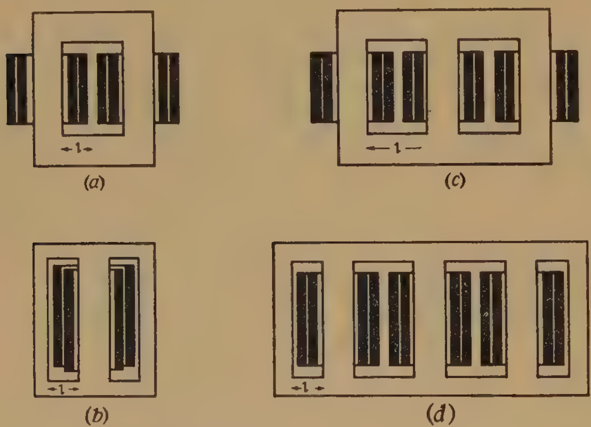


Fig. 4.—Principal winding arrangements for core-type transformers.
(a) Single-phase two-leg.
(b) Single-phase one-leg.
(c) Three-phase three-leg.
(d) Three-phase five-leg.

Fig. 4 shows the four principal winding arrangements of core-type transformers. A small axial displacement is drawn diagrammatically in Fig. 4(b). The effective displacement is not necessarily a physical movement of the whole winding but the resultant of the component asymmetries of the electromagnetic centres, and may be due to any of the items (a)–(k) of Section 3.

The stress for a simple dissymmetry, as shown in Fig. 4(b), is given by the formula

$$p = \frac{0\cdot 043L}{wal}\frac{S}{f}x \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where p is the stress per 1% axial displacement of the electromagnetic centres.

The difficult term in this formula is l, the effective length of the radial flux-leakage path. It is an important term in transformer design as it affects calculations of the reactance and eddy-current losses in the windings as well as the mechanical forces, and it has been much studied.[17–20] Fortunately, for the present purpose, we are concerned with the maximum stresses in the winding, and these will be where l is a minimum. This almost always occurs in the window of the core, where its usual value is simply as shown in Fig. 4. Thus the force is greatest on the part of the periphery of the windings in the window or under the yokes.[12, 15, 17] Short-circuit failures in service generally show this concentration. Fig. 5 shows a typical example.

Fig. 5.—Short-circuit failure of 60 MVA 132 kV transformer.

Incidentally, it will be seen from Fig. 4(c) that l for a single-phase fault (i.e. a fault to earth) on a 3-phase 3-leg transformer is much larger than for the other constructions, and this type of core is most favourable in this respect. For a transformer of the same rating and with the same windings but with a 5-leg core, as shown in Fig. 4(d), the mechanical stresses in the outer phases will be nearly doubled and the short-circuit strength correspondingly reduced.

The displacement force gives the maximum pressure at the ends of the winding against the yokes or clamping rings. The compressive force discussed in Section 7.1 gives the maximum pressure in the middle of the windings. In practical application the two formulae are combined to give a resultant axial force which may be a maximum towards either middle or ends—frequently the former initially and the latter eventually.

(7.3) Ideal Strength

The axial compressive strength considered in Section 7.1 can be represented by combining eqns. (4) and (5):

$$K_i^2 = \frac{0\cdot 022CL^2}{wlp} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

This has been termed the ideal strength because stresses due to winding dissymmetry and displacements in service are neglected. Since it is a purely axial compressive force, failure will nearly always occur in the middle of the winding.

(7.4) Initial Strength

Assume that the windings have an initial dissymmetry d_0 due to one or more of the causes (a)–(k) of Section 3.

Then, if K_0 is the initial breakdown strength,

$$K_0^2 p d_0 = C$$

whence $$K_0 = \sqrt{\frac{C}{pd_0}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Usually the combination of compressive and axial stresses referred to in Sections 7.1 and 7.2 gives a lower resultant strength than either K_i or K_0. The compressive force varies considerably in its distribution (a particular example is given in Fig. 4 of Reference 12) and in practice each case must be treated individually. Assuming in the middle of the winding the combination of the full compressive force and half the axial force, and using eqns. (7) and (12), the resultant initial strength K_0 can be found from the equation

$$\frac{1}{K_0'} = \sqrt{\left(\frac{0 \cdot 5}{K_0^2} + \frac{1}{K_i^2}\right)} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

This is the short-circuit strength of the transformer as normally calculated. It indicates the maximum strength under the short-circuit test prescribed in the national standard specifications. It will be shown later that this does not represent the strength of the transformer under operating conditions in service.

(7.5) Critical Strength

The axial stresses due to the initial displacement d_0 are repulsive and tend to force the windings further apart. The initial displacement d_0 increases to d_1. This leads to a larger force which, in turn, further increases the displacement. The final displacement is thus always larger than the initial value and may become out of control. Hence, also, the final stress is always larger than the initial stress and may become irresistible.

Thus, if the initial displacement is d_0 and the final value d,

$$C_1 = K^2 p_1 d$$

and $$C_2 = K^2 p_2 d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where the subscripts indicate the values for the two windings. The additional displacement due to the force is

$$d - d_0 = b_1 C_1 + b_2 C_2$$
$$= dK^2(p_1 b_1 + p_2 b_2)$$

whence $$d = \frac{d_0}{1 - K^2(p_1 b_1 + p_2 b_2)} \quad . \quad . \quad . \quad (10)$$

This is unstable, i.e. $d \to \infty$, when $K^2(p_1 b_1 + p_2 b_2) = 1$. Calling this the critical value of the strength, K_c, gives

$$K_c^2 = \frac{1}{p_1 b_1 + p_2 b_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

This is instability strength. It does not depend upon the initial displacement or on the mechanical strength C of the windings, clamps or supporting structure.

Hence a transformer perfectly designed and constructed, so far as mechanical support and electromagnetic balance of the windings are concerned, will not have an infinite mechanical strength but only the value K_c.

(7.6) Ultimate Strength

Since the transformer will, in practice, have some initial dissymmetry d_0, the strength in service will be not K_i, K_0 or K_c but some still lower value depending upon d_0 and the mechanical strength of the windings and their supporting structure.

Calling this ultimate strength K_1, then, from eqns. (7) and (9),

$$C = K_1^2 p_1 d = K_0^2 p_1 d_0$$

whence $$\frac{K_1^2}{K_0^2} = \frac{d_0}{d} = 1 - K_1^2(p_1 b_1 + p_2 b_2)$$ from eqn. (10)

$$= 1 - \frac{K_1^2}{K_c^2}$$ from eqn. (11).

This leads to the simple relation*

$$\frac{1}{K_1^2} = \frac{1}{K_c^2} + \frac{1}{K_0^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

or $$K_1^2 = \frac{K_c^2 K_0^2}{K_c^2 + K_0^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

The strength for the other winding or windings may be derived in the same way. The transformer's ultimate strength is the smallest of these values. It is, of course, the weakest winding which will fail in service.

(8) SUMMARY OF MECHANICAL-STRENGTH CATEGORIES

The foregoing development shows that the mechanical short-circuit strength of a transformer is not a simple single value, even when all the parameters are known and the formulae are correct. The various ways in which a transformer can fail mechanically under short-circuit conditions are summarized as follows:

Ideal Strength, K_i.—This is the mechanical strength assuming perfect design, perfect construction and perfect electromagnetic balance of the windings. There is practically no cumulative effect as the force increases little with movement of the windings. Failure usually occurs in the middle of the winding. This strength is mainly of academic interest but does serve as an interesting bench mark to show how far the practical values in service fall below the ideal. [Eqn. (6).]

Initial Strength, K_0.—This is the mechanical strength against a single short-circuit giving stresses equal to the crushing strength of the coils or insulating materials. No allowance is made for the displacement increasing and thus in turn increasing the stress. It is perhaps the best indication of the performance of the transformer under the short-circuit tests prescribed in national standard specifications. [Eqns. (7) or (8).]

Critical Strength, K_c.—If the force per unit displacement of the electromagnetic centres of the windings equals or exceeds the pressure per unit compression of the windings, the condition is unstable and the force will go on increasing until failure occurs irrespective (theoretically) of the mechanical strength of the windings or their supporting structure. The analogy mentioned in Section 7.2 is then reached of the egg standing on end.

A considerable number of faults or a prolonged short-circuit will be necessary before this limit is reached, and K_c is therefore the multi-short-circuit strength assuming perfect initial winding balance (i.e. $d_0 = 0$). [Eqn. (11).]

Ultimate Strength, K_1.—Since no transformer can be perfectly balanced in practice, owing to the various causes enumerated, (*a*)–(*k*) in Section 3, there will always be some initial dissymmetry d_0. The actual strengths for a large number of short-circuits will therefore be less than the critical value K_c due to this initial dissymmetry and will also depend upon the winding mechanical strength. [Eqn. (13).]

Radial Strength, K_r.—The limiting strength here is the tensile strength or the elongation characteristic of the conductor. It has not hitherto been treated in technical literature as being of serious consequence, but the analysis given in Section 6 shows that for the larger transformers now being built it may well be

* The compressive force (Section 7.3) tends to reduce this strength, but the effect is usually slight and is here neglected.

a limiting factor. It can be progressive in effect and thus affect the life of the transformer in service. Since its value is determined by the mechanical characteristics of the conductor there is little scope for control in design. [Eqn. (3).]

Service Stress, K_s.—The practical requirement with which all the foregoing strengths have to be compared is the short-circuit current which can occur in service. It depends, of course, on the supply system and transformer impedances and is frequently a complex calculation forming part of the system planning and sometimes having several values depending on circuit conditions. So far as the transformer manufacturer is concerned it is too frequently an unknown and unascertainable quantity. It may also increase in service for a particular transformer as the system capacity grows, as discussed in Section 2.

(9) PRACTICAL APPLICATION

Having developed relations for determining the various strengths, as distinct from formulae for calculating the individual forces, the next stage is to determine practical values of the parameters. The vital ones are p, b and C.

The first of these is discussed in Section 7.2 and obtained from appropriate mechanical-force formulae.[7–18] Owing to other requirements of design, reactance, losses, insulation, etc., the designer usually has little control over this parameter. The simple form in eqn. (5) shows that the area of insulation support, a, is the only effective variable and even this is limited by the need for oil cooling ducts.

In practice p varies from 0·004 to 0·05, the values generally being lower for the higher-voltage winding. It does not seem to vary significantly with the transformer rating.

(9.1) Mechanical Characteristics of Insulation

The effect, b, of the axial forces on the displacement of the windings is determined by the modulus of compression of the insulation. It is convenient here to use the inverse form c, which is the percentage compression of the insulating materials per ton per square inch pressure. The insulation consists of three parts: the conductor insulation t_1, the internal winding spacers and washers t_2, and the end insulation between the windings and the yokes t_3.

The force on the internal-winding insulation is cumulative, so that the effective value for the whole winding is one-third of the maximum.

The displacement of the electromagnetic centres per ton per square inch force then becomes

$$b = 0{\cdot}33(t_1c_1 + t_2c_2) + t_3c_3 \quad . \quad . \quad . \quad . \quad (14)$$

The fibrous materials generally used in winding insulation are far from being homogeneous bodies with linear mechanical characteristics, and there has been much study[18, 22, 32] of their plastic and rheological properties.

The behaviour depends much on the treatment and condition of the insulation, but, as a rough guide, Fig. 6 shows sample stress/strain curves for conductor covering, some grades of dry pressboard and a synthetic-resin varnished-paper (s.r.v.p.) board to B.S. 1137: 1949. The similarity, except for scale, between these curves and the corresponding curve for copper in Fig. 1 is interesting.

Conductor insulation is nowadays invariably paper wrapping. The inter-coil spacers and washers are generally pressboard to B.S. 231: 1950 types I and II or some form of synthetic-resin board.

Some measured values of the inverse modulus for these materials are given, as a guide, in Table 1, together with other published values and the corresponding limits of British Standards where available.

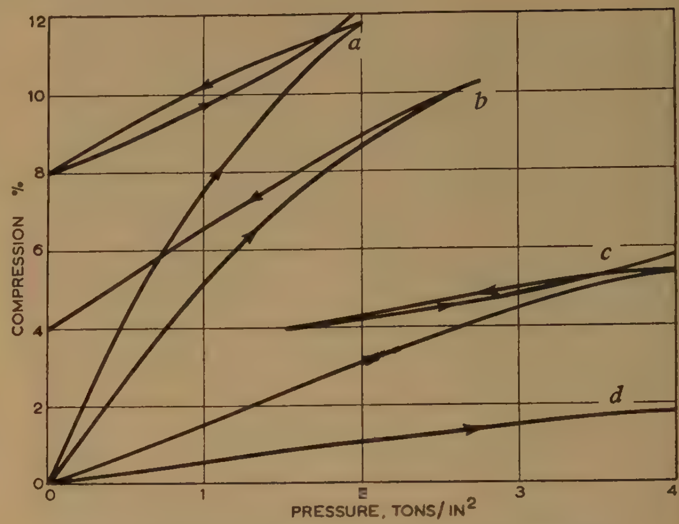


Fig. 6.—Stress/strain relations for transformer insulation.

Curve (*a*) Conductor paper covering.
Curve (*b*) Pressboard B.S. 231 : 1950 type II.
Curve (*c*) Hard Pressboard.
Curve (*d*) S.R.V.P. Board B.S. 1137 : 1949.

Table 1

PERCENTAGE COMPRESSION PER TON PER SQUARE INCH PRESSURE OF TRANSFORMER INSULATING MATERIALS

Pressboard:	
Soft board	5·8
Reference 18, Fig. 25	5·8
B.S. 231: 1950, type II	6·0
B.S. 231: 1950, type I	4·5
Reference 22	4·5
Hardboard, dry	1·8
Hardboard, oil-impregnated	1·3
S.R.V.P. boards	0·50
B.S. 1137: 1949	0·56
S.R.V.P. tubes	0·50
Synthetic-resin mouldings	0·3–0·5
Conductor paper covering	7·5
Reference 18	7·5

It is believed that it is the general practice for the spacer and washer insulation t_2 to be made of type II pressboard. Harder materials are not only more expensive and more difficult to shape but are also more difficult to impregnate completely—a vital matter in achieving maximum surge strength.

The values of b are obviously larger for the higher-voltage windings owing to the extra insulation, but do not seem to vary significantly with the size of transformer. Usual values range from 0·3 to 1·6, depending on the material.

(9.2) Mechanical Strength of Coil Stacks

Analysis of mechanical characteristics of the insulation, as in the previous Section, permits determination of the behaviour of the winding under short-circuit stresses but gives no indication of the end-point, i.e. the breakdown value. This can only be studied by tests, preferably full-scale, on stacks of coils built up exactly as in practical assembly of the transformer.

An extensive study of this kind has been carried out on many stacks of coils including the following variables:

(*a*) Thickness of the conductor insulation.
(*b*) Cross-section of the conductor.
(*c*) Transposition of strands.
(*d*) Type of spacing material.
(*e*) Type of winding disc, helical, etc.

Each stack was mounted in a hydraulic press. The pressure was applied slowly and steadily, and continuous records of pressure, compression, time and behaviour of the winding were photographed by a slow-motion ciné film. The interrelation of these characteristics could then be analysed in detail by study of the film.

Short-circuits between strands were indicated on an ammeter by changes in current flow.

The criterion of failure depended not only on these records but also on a number of observers stationed around the press who indicated the point of failure on the film by a lamp signalling code. Failure was defined as any actual breakdown between turns or strands or as the first sign of any form of distortion of the coils apart from straightforward compression. A typical stress/strain relation is shown in Fig. 7 for (*a*) a stack of disc coils using a square 0·28 in × 0·28 in conductor with ¼ in ducts between coils, and (*b*) a single-layer helical coil with thirteen 0·125 in × 0·225 in conductors in parallel.

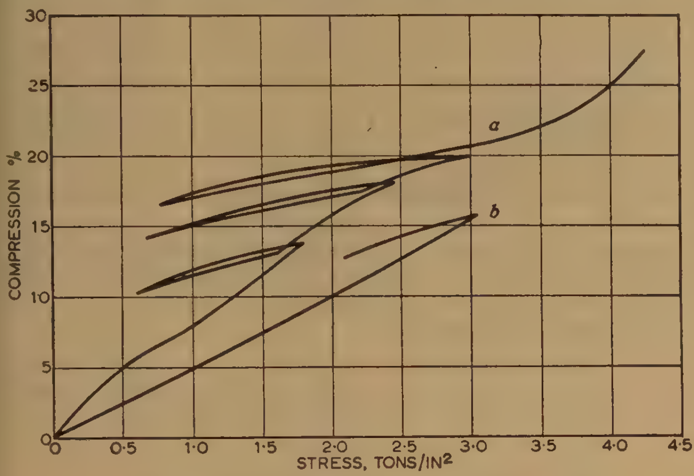


Fig. 7.—Stress/strain relations for stacks of coils.

(*a*) Disc winding, 0·28 in × 0·28 in conductor, ¼ in ducts between coils.
(*b*) Single-layer helical coil. 13 conductors 0·125 in × 0·225 in—parallel.

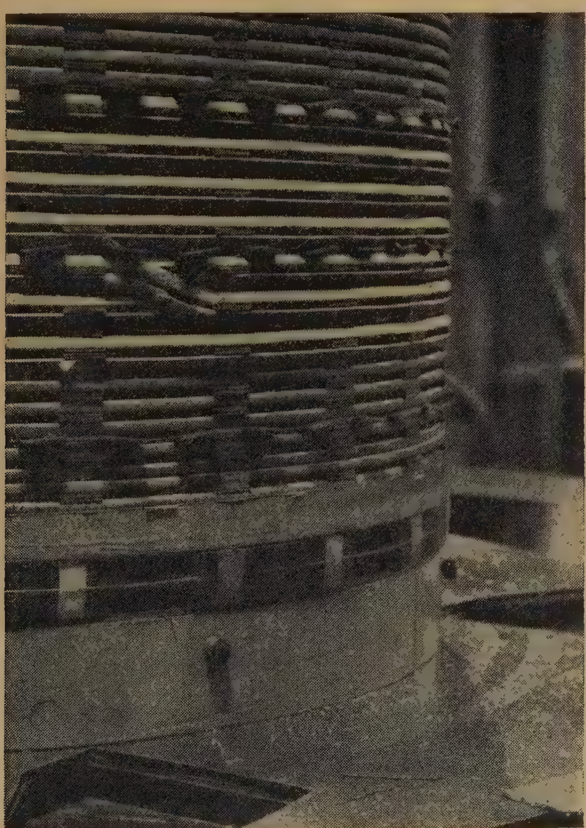


Fig. 8.—Mechanical failure of 60 MVA transformer l.v. winding.

The weakest point was frequently a tendency for the conductors to turn over. That this is representative of incipient failure in service is shown by Fig. 8, which is taken from a short-circuit failure of a 60 MVA 132 kV transformer.

From these tests, values of C range from 2·0 to 4·0 tons/in², depending on the factors (*a*)–(*e*) above. Less meticulousness in observation would have led to more favourable results.

(9.3) Typical Values of Mechanical Strengths

It will be shown in Section 10 that actual values of the various short-circuit strengths vary over a wide range. In order to give a general picture of the various values and to show their interrelation and dependence on the insulation, characteristic curves have been plotted in Figs. 9, 10 and 11. Fig. 9 shows the effect

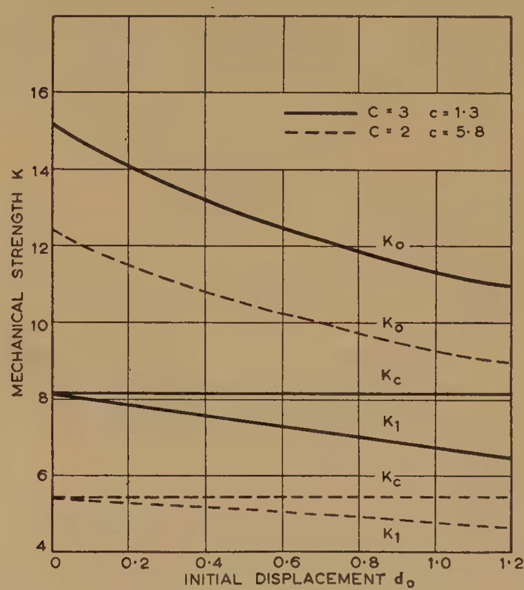


Fig. 9.—Effect of initial dissymmetry on winding strength.

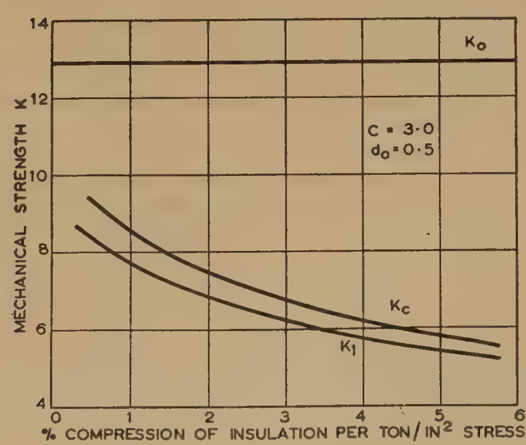


Fig. 10.—Effect of quality of intercoil insulation on winding strength.

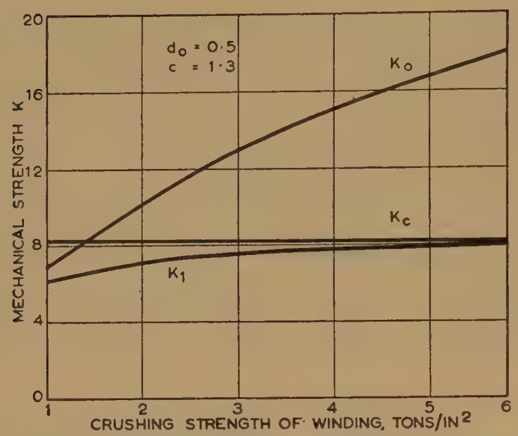


Fig. 11.—Effect of crushing strength of coil stack on winding strength.

of initial asymmetry of the electromagnetic centres of the windings for two grades of pressboard spacers taken from Table 1; Fig. 10 shows the effect of insulation mechanical strength; and Fig. 11 shows the dependence upon the crushing strength of the coil stacks, as studied in the previous Section.

As a final example, six typical designs of 3-phase 3-limb transformers are compared in Table 2. Two coil-stack strengths

Table 2

Typical Transformer Mechanical Strengths

Coil stack strength C..	3	3	3	3	2	2	14
Coil insulation	*a*	*b*	*b*	*c*	*a*	*b*	*d*
Initial displacement, d_0	0·5	0	0·5	0·5	0·5	0·5	0·5
K_i	15·2	15·2	15·2	15·2	12·4	12·4	33
K_0	12·9	15·2	12·9	12·9	10·5	10·5	27·9
K_c	5·4	8·15	8·15	9·2	5·4	8·15	12·3
K_1	5·2	8·15	7·4	8·1	5·1	7·1	11·7

($C = 2{\cdot}0$ and $3{\cdot}0$) are assumed and three types of coil insulation: (*a*) a British Standard type II pressboard with $c = 5{\cdot}8$, (*b*) a hard pressboard with $c = 1{\cdot}3$, and (*c*) a synthetic resin varnished paperboard with $c = 0{\cdot}5$. The effect of initial electromagnetic asymmetries of zero and $0{\cdot}5\%$ is also included.

Study of these curves and examples leads to the following generalized conclusions from the hypothetical parameters:

(i) The ideal strength K_i is ample for all designs.

(ii) Provided that the transformer reactance is over 10%, all designs will pass the standard short-circuit tests of the national standard specifications. This is true even where the usual soft pressboard is used.

(iii) No designs will be completely short-circuit proof in service unless the transformer reactance is well over 12%. This is true even if the windings are perfectly balanced initially ($d_0 = 0$).

(iv) Notwithstanding (iii) many transformers will still have satisfactory life in service.

(v) The lower coil-stack strength reduces the resistance to single short-circuits, K_0, but has little effect on the multi-short-circuit service strength, K_1 (Fig. 15).

(vi) The standard short-circuit tests, therefore, are sensitive to the coil-stack strength or initial dissymmetry (Fig. 9), but give little indication of the performance in service, K_1.

(vii) There is no marked dependence of strength on apparent-power rating. Dimensionally the strengths K are inversely proportional to (kilovolt-amperes)$^{0{\cdot}125}$, from eqns. (5) and (7). This slight dependence is apparently obscured by other factors, one of which is referred to in Section 6.2.1.

(viii) The life in service depends largely upon the compression modulus of the insulation, i.e. the values of c as given in Table 1 (Fig. 10).

(10) EXPECTATION OF LIFE

The cumulative effect of successive short-circuits has been developed in Section 7, and the extreme values have been derived of strength K_0 for a single short-circuit and of strength K_1 for a large number of faults.

In this Section an attempt is made to interpolate between these extremes and obtain a method of determining the number of short-circuits a given transformer will withstand under operating conditions in service—in other words, the mechanical life of the transformer.

It must be admitted here that the process involves plausible hypotheses and engineering judgment rather than technical precision, and its justification will lie in the extent to which it is ratified by the available evidence of short-circuit behaviour in service dealt with in the next Section.

From eqns. (10) and (11),

$$\frac{d}{d_0} = \frac{1}{1 - K_s^2(p_1b_1 + p_2b_2)} = \frac{1}{1 - \dfrac{K_s^2}{K_c^2}} = \frac{K_0^2}{K_s^2} \quad . \quad (15)$$

This can be expanded as a geometrical progression* into:

$$\frac{K_0^2}{K_s^2} = 1 + \left(\frac{K_s}{K_c}\right)^2 + \left(\frac{K_s}{K_c}\right)^4 + \left(\frac{K_s}{K_c}\right)^6 + \ldots$$

Considering each term of this progression as a unit of life in service, and if N is the number of terms,

$$\frac{K_0^2}{K_s^2} = \frac{\left(\dfrac{K_s}{K_c}\right)^{2N} - 1}{\left(\dfrac{K_s}{K_c}\right)^2 - 1}$$

whence

$$N = \frac{\log\left(1 + \dfrac{K_0^2}{K_c^2} - \dfrac{K_0^2}{K_s^2}\right)}{\log\left(\dfrac{K_s}{K_c}\right)^2} \quad . \quad . \quad . \quad . \quad (16)$$

These relations are shown in Fig. 12.

The analysis of operating records described in the next Section indicates that each of the N terms corresponds to nine normal short-circuits as recorded by operating engineers in service. Hence this latter number $n = 9N$. This factor is made up of two components: (*a*) the number of short-circuits of full asymmetrical value K_s in each N term, and (*b*) the number of nominal faults as given in service records corresponding to one short-circuit of full asymmetrical value K_s.

This calibration is probably on the safe or pessimistic side, because most of the service records are some years old and short-circuits are now cleared more quickly and with better discrimination. On the other hand, this is offset more or less by the modern developments referred to in Section 2.

As an example, consider a transformer complying with the third column of Table 2. For a short-circuit of 12·9 times full load it will just withstand the standard short-circuit test or,

* The same formula would be derived by a step-by-step process of calculating the progressive strain due to successive short-circuits.

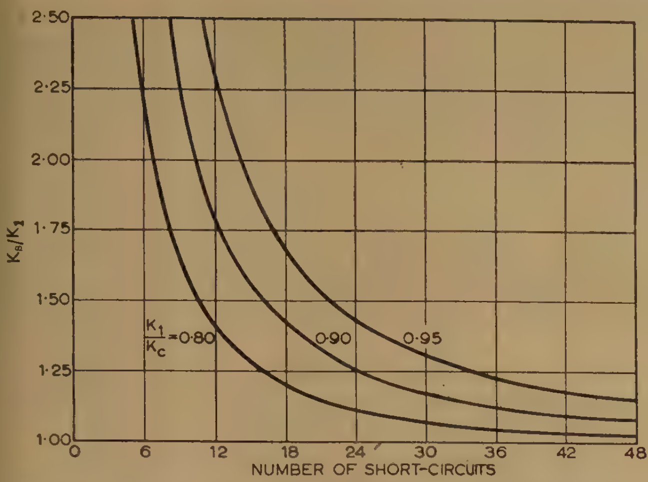


Fig. 12.—Effect of short-circuit stress in service on transformer life.

alternatively, nine nominal faults in service. At 8·15 times full load it will withstand 40 nominal faults and at 7·4 times full load an unlimited number of faults.

Curves showing the relative lives for various conditions and for coil insulation as stated in Table 2 are plotted in Fig. 13, the maximum value again being K_0'.

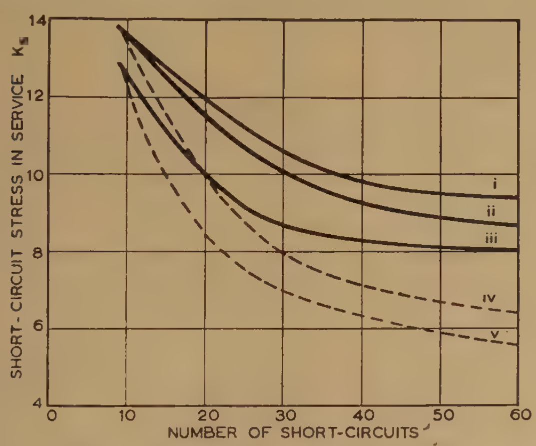


Fig. 13.—Typical values of short-circuit stress and life of transformer in service.

Curve (i) $d_0 = 0{\cdot}25$, coil insulation = *c* (from Table 2).
Curve (ii) $d_0 = 0{\cdot}25$, coil insulation = *b*.
Curve (iii) $d_0 = 0{\cdot}50$, coil insulation = *b*.
Curve (iv) $d_0 = 0{\cdot}25$, coil insulation = *a*.
Curve (v) $d_0 = 0{\cdot}50$, coil insulation = *a*.

The service analysis in the next Section suggests a standard deviation of 30% in the distribution of life values. Thus, if the calculated life is 20 short-circuits, the chances are 1 : 40 that it will withstand 32 short-circuits and 40 : 1 that it will withstand at least 8 faults.

(11) PERFORMANCE IN SERVICE

It is very difficult to obtain practical evidence of the performance of power transformers in service as far as short-circuit stresses are concerned. In a modern well-run system, dead short-circuits are rare—rates have been suggested to the author varying from 0·1 to 1·0 per transformer per annum. Other factors making failures specifically attributable to mechanical stresses difficult to identify are referred to in Section 1.

(11.1) Analysis of Failures in Service

The practical evidence the author has been able to collect (summarized in Table 3) is mostly provided by two periods of exceptional—in fact, freakish—operating conditions, outside normal practical possibilities.

Table 3

Records of Mechanical Failures

Case	MVA	K_s/K_1	K_1/K_c	*n* (calculated)	*n* (actual)
A	60	1·66	0·71	6·5	14
B	60	1·66	0·71	6·5	5
C	60	1·66	0·71	6·5	3
D	60	1·33	0·88	16	14
E	60	1·00	0·81	∞	
F	30	1·21	0·91	26	23
G	30	1·21	0·91	26	28
H	30	0·88	0·84	∞	
J	60	1·46	0·84	13	16
K	60	1·20	0·96	44	33 (*a*)
L	20	1·10	0·88	34	28 (*b*)
M	20	1·10	0·88	34	28 (*b*)
N	80	1·00	0·80	∞	
O	80	1·96	0·80	7	3–9
P	40	1·25	0·86	20	9–15
Q	20	1·92	0·88	10	(*c*)
R	2·5	1·48	0·89	15	(*d*)

(*a*) No failure occurred.
(*b*) Partial failure.
(*c*) Failed after 8 years' service.
(*d*) Failed after 9 years' service.

Values in this Table are calculated from accurate design formulae taking full account of the complex winding characteristics of a large power transformer—not from the simplified formulae given in the paper. The value of initial axial displacement of the electromagnetic centres assumed is the design value if that is greater than 0·5%, and 0·5% if it is less, to allow for actual possible displacements in assembly.

Cases A, B, C concern three transformers, designed in 1929, with an electromagnetic displacement due to difference in ampere-turn distribution of 0·8 in, or 1·2%. After these failures this dissymmetry was corrected and case D resulted. The damaged transformers were rewound with balanced windings (on paper) and a harder type of pressboard for the coil washers and spacers. Case E shows the resulting improvements. No failures have occurred on these transformers.

Cases F and G refer to two transformers feeding the two circuits of a double-circuit line. These transformers, like the previous ones, had two periods of abnormal operation, as shown in the short-circuit history of one of them plotted in Fig. 14. The group of short-circuits in the early years was due to excessive fog flashovers, as recorded in Fig. 15 of Reference 23. There followed a period of normal service and then another abnormal period of short-circuits due to trailing barrage-balloon cables accentuated by an unusually exposed position of the substation.

The normal operation condition, as shown by the dotted line in the Figure, indicates a normal short-circuit life of 54 years. When these transformers were rewound the improvement shown in Case H was made, owing to development in design in the intervening 12 years.

Cases L and M, concerning two transformers in parallel, are of particular interest since partial failure due to short-circuit stresses was detected before actual failure, so that the mechanical strains were not obscured by breakdown damage.

These two transformers were designed for parallel-winding on-load tap-changing gear. A differential current transformer

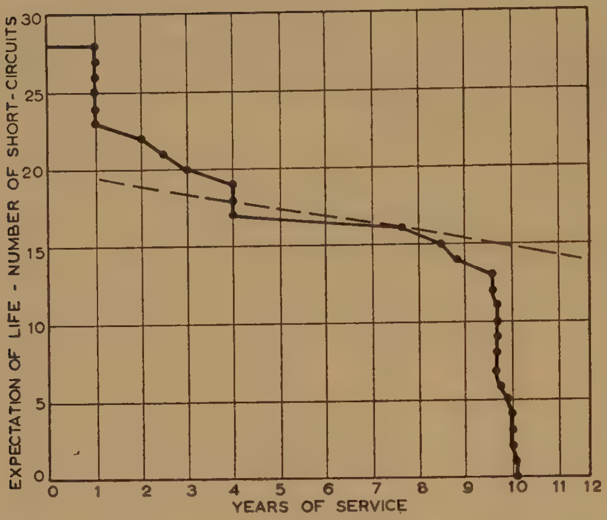


Fig. 14.—Service record of short-circuits on 30 MVA transformer.

Dotted line indicates normal operating conditions showing an expected life of 54 years.

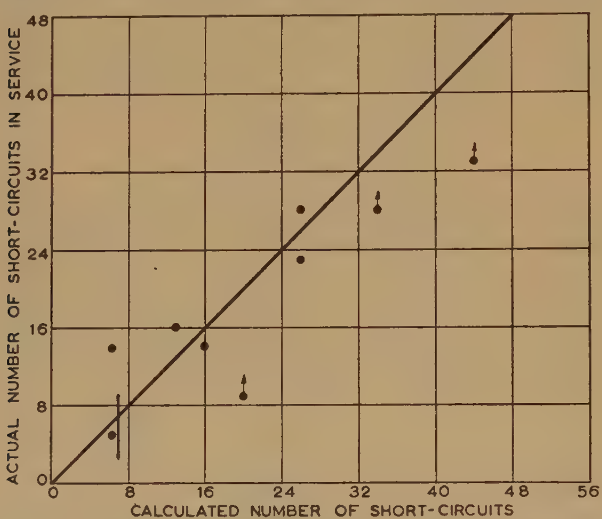


Fig. 15.—Relation between calculated and actual number of short-circuits from service records.

was connected in the parallel halves to detect differences in current in the course of tap-changing. Since the parallel halves cannot be perfectly balanced there is a negligibly small 'spill' current during normal operation. This current was recorded periodically, and after a time a gradual increase was noticed. This was caused by a small movement of the windings due to short-circuit stresses—a movement that superficial examination in service would not have detected. The movements were found on all six phases in differing degrees, thus emphasizing the progressive nature of the strains due to short-circuits. These transformers had also had a very severe short-circuit history. Rectification was thus possible before damage had been done.

Cases N and O concern a transformer which had undergone a short-circuit test.[5] The working condition is shown at N and the short-circuit test condition at O. The failure during the short-circuit test—which was accentuated well beyond the service condition, though still within the full infinite-power value—is predicted by the calculations.

Case P also deals with a short-circuit test.[4] This transformer passed the test—again in accordance with prediction.

In most cases one of the windings is mechanically weaker than the other, and values in the Table are given for this winding. In Case Q the calculated strengths of both windings (this was a single concentric transformer) were the same within a few per cent. When the transformer was examined both windings were found to have failed.

Case R was unusual in that failure occurred in a tertiary winding—again as calculated. In Cases Q and R no record of the number of short-circuits was available, but the ages of the transformers are given as some guide to the service life.

The results of all this service experience in supporting the method of predetermining the short-circuit strength are assembled in Fig. 15. These results as a whole are perhaps somewhat pessimistic in relation to present-day manufacture, because all of the transformers concerned were designed over 25 years ago.

Analysis of Table 3 leads to the following conclusions:

(*a*) None of the transformers failed in service unless predicted by the calculations.
(*b*) All failures occurred in the winding calculated to be weakest mechanically.
(*c*) In Case F, where two windings were calculated to be equally weak, both failed.
(*d*) Of the two transformers short-circuit tested, one failed and one withstood the test—both as predicted.
(*e*) The increase in life through improving the electromagnetic balances in the windings was as calculated (Case D).
(*f*) In Cases F and G failure occurred in the h.v. winding instead of the more usual l.v. winding—again as predicted.
(*g*) The progressive nature of short-circuit failure in service is shown clearly in Cases L and M.
(*h*) The predicted life agrees with the actual life to the degree shown in Fig. 15.

(11.2) Expectation of Life in Service

A preliminary estimate of the expectation of life of a transformer may be made by considering, in each particular case, the local severity of short-circuits, i.e. the value of K_s, and the local frequency of short-circuits per annum. The expected life in years can then be deduced from eqn. (16). It is likely that in the majority of cases this study will give a satisfactory assurance of long service, and short-circuit stresses need not be considered a serious matter.

Where there seems to be a practical limitation, or where the actual faults in service are unusually frequent or serious, a record can be kept, as shown in Fig. 14. Taking this as an example, the transformer had a normal life of 54 years (Section 11.1, Case G). It used up 19·3 years of this expected life in the first 3·5 years of actual service and 31 years in the last 2·5 years of service. This was, of course, an abnormal case and far from representative of practical operating conditions, but it illustrates the method suggested.

(11.3) Possibilities of Improvement

The radial strength K_r considered in Section 6 is not usually a practical limitation, and technical literature does not suggest that safe tensile stresses in the copper (Section 6.2) have hitherto been exceeded in practical operation. Although the damage, i.e. the strain, due to the radial forces may be progressive, as explained in Section 6.2.1, the stresses are not cumulative, as in the axial strength, so that the ultimate conditions are more definitely circumscribed.

The axial strength K_1 can be increased by any of the means described in Section 9, and these methods have accounted for the generally satisfactory performance of large power transformers in service, especially where the frequency of short-circuit faults is within the limits normally imposed by good operating practice.

Two limits inherent in the normal construction are the crushing strength of the coil stack C, which is necessarily much lower than

that of the supporting insulation and structural work (roughly in the ratio 1 : 5), and the compression modulus of the conductor covering, which is much lower than that of the coil spacers and washers and the end insulation (compare values of c in Table 1). If, therefore, a construction is employed whereby the building up of force from coil to coil in the winding is eliminated, the short-circuit strength of the transformer will no longer be limited by the relatively weak mechanical characteristics of soft copper conductors and fibrous paper insulation.

This result can be achieved by supporting each coil individually and independently of the remaining coils by bridging pieces, as shown in Fig. 16. The forces of each coil are then transferred to

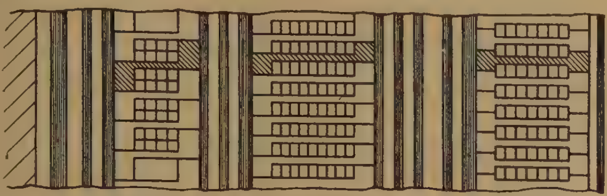


Fig. 16.—Cross-section of windings showing 'bridge' construction.

a number of solid columns of insulation which can be designed to meet the required mechanical stresses free from limitations imposed by electrical and technical winding considerations. This 'bridge' construction[4] naturally increases the size and cost of the transformer and is not normally necessary, but it can be employed when required to meet particularly severe operating conditions. A typical example of the improvement obtainable is given in column 7 of Table 2.

(12) STANDARD SHORT-CIRCUIT RATINGS

Reference has been made in Section 2 to the short-circuit ratings prescribed in national standard specifications such as References 25, 26 and 27. The relevant clauses stipulate that the transformer must be capable of withstanding a short-circuit on its terminals with full line voltage maintained on the supply side.

This rating is unrepresentative of practical operating conditions in two major respects. In one of them it is much too severe, and in the other too lenient. Unfortunately the severity and the leniency do not cancel.

(*a*) The requirement that full line voltage must be maintained means a supply system of zero impedance, i.e. of infinite capacity. This is, of course, impossible. The test is also impracticable, as short-circuit testing stations do not exist[1] of sufficient size to carry out such tests on large power transformers. This is recognized in the I.E.C. Recommendations,[25] and in other cases no actual test is specified even as a special or type test. Most specifications allow the inclusion of the impedance of 'direct-connected apparatus' either as part of the specification or by agreement with the purchaser. This permits, for example, the inclusion of the generator impedance for generator-transformer units.

It is suggested that the minimum external impedance, including direct-connected apparatus and the supply-system impedance, shall be specified by the purchaser and the resulting short-circuit rating marked on the name-plate.

(*b*) The specifications call for a single short-circuit. A duration is also specified, but that concerns the thermal effects of the short-circuit and not the mechanical stresses. The strength for a single short-circuit corresponds to K_0 in Section 8, and this is shown in Tables 2 and Figs. 9–11 to be, in general, much higher than the strength K_1 for a number of short-circuits. The implication, therefore, in the national standards that a transformer complying with the specification is necessarily, or even probably, short-circuit proof in service is false.

Owing to the progressive and cumulative nature of the stresses, a number of fully asymmetrical short-circuits are required in any short-circuit test if the results are to be conclusive. At least 10 are suggested, suitably spaced to avoid excess temperatures. It is also necessary that after the test the windings shall be dismantled and carefully examined for signs of damage or coil distortion.

If these stringencies make short-circuit tests more difficult they will, at least, not result in fewer being made than hitherto.

(13) CONCLUSIONS

(*a*) The mechanical strength of a transformer under short-circuit is not a simple single value as is generally assumed, even when the formulae are correct and all the parameters are known both for design and for service conditions. Some of the strains are progressive and some of the stresses cumulative, leading to short-term and long-term characteristics. The resulting performance in service depends on analysis of these various strengths (Sections 6–8).

(*b*) It is shown from this analysis how the mechanical behaviour of the transformer in service can be predetermined (Section 9).

(*c*) Records from operating experience of short-circuit failures in service have been compared with the calculated values and parameters deduced therefrom, enabling the expectation of life in service to be estimated (Sections 6 and 10).

(*d*) By recording the actual short-circuits in service the remaining expectation of life can be continuously reviewed (Fig. 14).

(*e*) Operating experience has, in general, shown that present-day practice in the design and construction of large power transformers is satisfactory hitherto as far as short-circuit stresses are concerned.

(*f*) Additional strength can be obtained when necessary to meet unusually severe conditions (Section 11.3).

(*g*) The standard short-circuit rating prescribed in national standard specifications[25, 26, 27] is inadequate and may be quite misleading, as it gives little or no indication of the performance of the transformer under short-circuit conditions in service (Section 12).

(*h*) For the reasons detailed in Section 2, short-circuit stresses are becoming of increasing frequency and severity, making the mechanical strength of large power transformers and their expectation of life a matter of serious concern.

(14) ACKNOWLEDGMENTS

Acknowledgments and thanks are due to the Central Electricity Authority and to various other supply authorities for the service records of short-circuits on power transformers which are summarized in Table 3; to the Copper Development Association for information on the stress/strain characteristics of copper; to Mr. F. W. Gee and Mr. H. R. Heap for the experimental work on stacks of windings and insulating materials, respectively, and to Ferranti Ltd. for permission to publish the paper.

(15) BIBLIOGRAPHY

(1) STENKVIST, E., and TORSEKA, L.: 'What is Known about the Ability of Large Power Transformers to Withstand a Short-Circuit. Comments for Existing Practice', C.I.G.R.É., Paris, 1956, Paper No. 106.

(2) CHEVALIER, H., and GRANDY, E.: 'Transformateurs de puissance à très haute tension', *ACEC Review*, 1952, **4**, p. 30.

(3) NORRIS, E. T.: 'Short-Circuit Tests on 80 000 kVA Units', *Electrician*, 1935, **114**, p. 767.

(4) Norris, E. T.: 'Mechanical Strength of Large Power Transformers', *World Power*, 1935, **24**, p. 292.
(5) Norris, E. T.: 'Short-Circuit Tests', *Electrician*, 1925, **94**, pp. 456 and 459.
(6) Lacey, H. M.: 'Short-Circuit Forces in Transformers', *Co-operative Electrical Research*, No. 1.
(7) Moody, W. S., and Boyajian, A.: 'Mechanical Forces in Transformers', *General Electric Review*, 1927, **30**, p. 420.
(8) Clem, J. E.: 'Mechanical Forces in Transformers', *Transactions of the American I.E.E.*, 1927, **46**, p. 814.
(9) Waters, M.: 'Mechanical Stresses in Transformer Windings', E.R.A. Report Q/T101A.
(10) Billig, E.: 'Displacements in Windings of a 45 mVA Transformer. Calculation of Associated Electromagnetic Forces', E.R.A. Report Q/T105.
(11) Waters, M.: 'Measurement of Axial Forces in Transformer Windings', E.R.A. Report Q/T113.
(12) Waters, M.: 'Measurement and Calculation of Axial Electromagnetic Forces in Concentric Transformer Windings', E.R.A. Report Q/T134.
(13) Waters, M.: 'Electromagnetic Forces in Transformers with Multi-Layer Windings', E.R.A. Report Q/T143.
(14) Waters, M.: 'Effect of Core Proportions on Axial Electromagnetic Forces in Transformers with Concentric Windings', E.R.A. Report Q/T144.
(15) de Kuijper, C. E. M.: 'Short-Circuit Forces in Symmetrical Windings of Transformers', C.I.G.R.É., Paris, 1952, Paper No. 122.
(16) Billig, E.: 'Mechanical Stresses in Transformer Windings', *Journal I.E.E.*, 1946, **93**, Part II, p. 227.
(17) Fergestad, R.: 'Electromagnetic Forces in Core-Type Transformers with Concentric Windings', C.I.G.R.É., Paris, 1956, Paper No. 114.
(18) Knaack, W.: 'Mechanical Stressing of Transformer Windings upon Short-Circuit', *ibid.*, Paper No. 135.
(19) Waters, M.: 'Reactance and Stray Losses due to Radial Leakage Fields in Transformers with Concentric Windings', E.R.A. Report Q/T146.
(20) Morris, A. L.: 'Influence of Various Factors upon the Leakage Reactance of Transformers', *Journal I.E.E.*, 1940, **86**, p. 485.
(21) Young, J. F., and Lambert, J. B.: 'Mechanical Performance of Metals', *General Electric Review*, 1943, **46**, p. 669.
(22) 'The Behaviour of Pressboard under Compression', E.R.A. Report L/T174.
(23) Johnstone Wright: Presidential Address, *Journal I.E.E.*, 1940, **86**, p. 1 (Fig. 15).
(24) Fischer, E.: 'Die Festigkeit der inneren Röhre von Transformatoren-Wicklungen', *ETZ—A*, 1952, **73**, p. 121.
(25) 'I.E.C. Recommendations for Power Transformers', Publication 76, Clause 801.
(26) 'American Standards for Transformers', C.57.12: 1948, Clause 12050.
(27) 'Power Transformers', B.S. 171: 1936, Clause 16.
(28) Norris, E. T.: 'Relations between the Manufacturer and Purchaser of Electrical Equipment', *Journal I.E.E.*, 1946, **93**, Part 1, p. 37.
(29) Casson, W., and Gunning, P. F.: 'Methods and Channels for Control and Inter-Tripping on the British Grid System', C.I.G.R.É., Paris, 1956, Paper No. 307.
(30) Smith, C. S., and Van Wagner, R. W.: 'The Tensile Properties of Some Copper Alloys', *Proceedings of the American Society for Testing Metals*, 1941, **41**, p. 825.
(31) Benson, N. D., McKeown, J., and Mends, D. N.: 'The Creep and Softening Properties of Copper for Alternator Rotor Windings', *Journal of the Institute of Metals*, 1954, **80**, Part 3, p. 131.
(32) 'Effect of Compression, Humidity and Temperature on Transformer Pressboard', E.R.A. Report L/T363 (unpublished).

DISCUSSION BEFORE THE SUPPLY SECTION, 27TH FEBRUARY, 1957

Sir John Hacking: I am particularly glad to open this discussion as at one stage in the early operation of the 132 kV Grid in this country the author and I were trying to account for an epidemic of failures on 132 kV transformers, particularly of 60 MVA capacity. I think these must have been the transformers described as Cases A, B and C in Table 3 of the paper.

Even before the British Grid came into operation the author was largely instrumental in making a very substantial economy in its construction and operational costs. Most manufacturers at that time were strongly in favour of the use of banks of single-phase transformers with their necessarily relatively high costs. In this they were influenced largely by the anticipated difficulty of transporting large 3-phase units over British railways and roads. I recollect that the author and the firm for which he worked were the first to express their readiness to build 60 MVA 3-phase units, this being the maximum capacity then contemplated. By doing this they enabled substantial economies to be made in the construction of the Grid.

The early operation of the 132 kV Grid was rendered unexpectedly difficult by large numbers of insulation flashovers in foggy or misty weather conditions. Insulation theory at that time was to put as long a leakage path as possible in a protected place where the rain could not easily get at it. The result was an insulator with several relatively shallow corrugations on the inside. It was largely protected from the weather and particularly from the rain. Because horizontal insulators could not be protected in this way it was considered necessary to have longer leakage paths for tension units, and this was done by increasing the number of units per string in such situations.

In practice, the shallow corrugations in the suspension units became rapidly coated with a thick deposit of dirt, particularly in industrial areas, and in misty weather the resistance of these surfaces was much reduced and flashovers resulted. The tension insulators which were horizontally mounted in the line of the conductors were kept clear of dirt by the rain which had ready access to the underside of such units. The result was that whilst the vertically mounted units flashed over the horizontally mounted units did not.

Before the necessary remedial measures were taken there were very many flashovers with consequent severe mechanical shocks to the transformers. These conditions resulted in occasional mechanical failures of transformers. That lessons were learnt by the transformer designers is shown by the summary of the careful analyses of experience given in the paper.

I think the mathematical analysis of the problem is very well summarized in the curves of Fig. 12, provided that we remember that (i) the ordinates indicate the ratio between the possible short-circuit apparent power (kVA) in the particular location considered and the long-term safe short-circuit apparent power (MVA) for the transformer, and (ii) the three curves illustrate different conditions of initial out-of-balance.

It is, however, necessary to draw only very tentative conclusions, and I strongly endorse the warning given by the author in the third paragraph of Section 10. It is obvious that the curves

must be interpreted with considerable caution, although study of them does draw attention to two possible ways of easing this particular duty on transformers, namely

(i) The design of transformers for a reasonably high reactance, the disadvantage of which can be compensated for in the range of on-load tapping regulation.

(ii) The desirability of limiting the short-circuit apparent power on the system, excluding the reactance of the transformer itself.

The latter method is not so easy, but when one contemplates the possible figure of 25 000 MVA or more given in Section 3, it will clearly be worthy of consideration in the future.

I was very interested in the construction shown by the author in Fig. 16. If and when we get to short-circuit apparent powers approaching 25 000 MVA I should think it would be worth while to accept the higher cost of such a construction.

I would like to comment in a lighter vein on the use the author makes in two places of the egg standing on end as a symbol of unstable equilibrium. This might be a valid comparison if the stress on the transformer were continuously—and perhaps increasingly—applied, but it does not seem to be to be valid when we consider a series of shocks on this piece of apparatus. It seems to me only to be applicable to the last shock which causes the final failure.

Mr. L. C. Richards: Maximum forces occur if a short-circuit takes place as the voltage wave is passing through zero, as this produces maximum asymmetry in the current wave and a force which is approximately three times that due to a symmetric wave. The trouble may be accentuated if the primary circuit-breaker is closed when there is a fault on the secondary, since a large magnetizing current may be superimposed on a fully asymmetric fault current with consequent increases in the forces available.

On the other hand, the chance of a fully asymmetric short-circuit occurring on a high-voltage system is reduced, because an arc will probably precede actual contact and the arc will not strike at zero voltage. As large transformers are often high-voltage they will not, therefore, generally be called upon to withstand the worst effects of short-circuit.

The mechanical failures recorded in Table 3 occurred many years ago, and I hope this implies that modern transformers are more reliable in operation than their predecessors. It is to be expected that the techniques of insulation and coil shrinkage, coil clamping and design of windings to withstand maximum short-circuit forces are now fully understood by all manufacturers.

It is appreciated that short-circuit tests cannot be carried out on the largest sizes of transformers, owing to the limited capacities of test plants, and that in any case the full effects thereof could only be determined by subsequently dismantling the transformer. It would thus appear that the question of providing a reliable transformer will have to be left, as hitherto, to the skill of the designer and builder, and modern experience would indicate that if this is done a satisfactory result will be obtained.

Mr. M. Waters: In calculating the axial compressive strengths, the author assumes the windings to consist of elastic columns, clamped so as to be firmly held, but without deliberate initial compression. One school of thought holds that windings should be clamped so as to have initial stresses greater than any which could occur in service, and it is important to ascertain if there is anything to be gained by initial axial compression applied by the end rings.

Consider two similar windings with an axial displacement d_0 as shown in Fig. A(i) when no current is flowing. On short-circuit the windings are compressed, giving an increased displacement d as shown in Fig. A(ii). The distribution of axial stress along the windings is shown in Fig. A(iii). Suppose now that the end rings are moved axially towards each other, e.g. by means of jack screws, until the gap length $d - d_0$ disappears. The

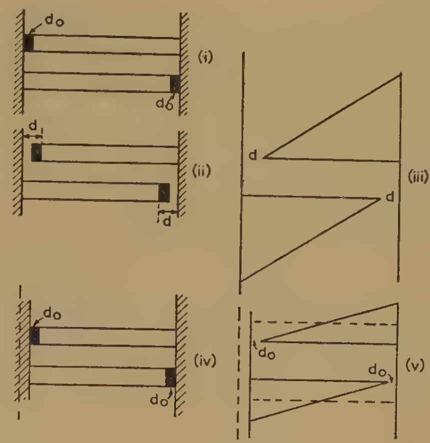


Fig. A.—Effect of initial compression on axial electromagnetic forces.

axial displacement is reduced to its original value d_0, as shown in Fig. A(iv), and the axial force is reduced in the ratio d_0/d, giving reduced stress, as shown in Fig. A(v). In this condition each winding is exerting a force corresponding to d_0 on one end ring and no force on the other.

If the short-circuit is now removed the electromagnetic forces disappear, and the compressed windings try to expand, producing forces against the end rings. The compressive force must now be the same at all points along the winding, and calculation shows that the force exerted at each end of one winding has half the magnitude of the electromagnetic force due to the displacement d_0, as shown by the dotted lines in Fig. A(v). It is clear, therefore, that in theory the application of an initial axial compression can help to reduce axial forces by reducing axial movement of the windings.

If the simple arrangement of windings shown in Fig. A is given an initial stress greater than half the crushing stress, then $d = d_0$ for all stresses up to the crushing strength, and failure must always occur before d can exceed d_0. Thus there is no longer a critical strength and the ultimate strength K_1 is equal to the initial strength K_0, which of course is greater than the ultimate strength without initial compression.

In Fig. A the windings are touching the end rings so that no movement can take place, but in an actual transformer end insulation must be used between the windings and the end rings and initial stressing cannot prevent the compression of this and subsequent movement of the windings. Thus, only with incompressible end insulation could $d = d_0$ for all stresses and $K_1 = K_0$. With compressible end insulation there must always be a critical strength K_c, and K_1 will always be less than K_0, but K_c when there is appropriate initial compression depends upon the compressibility of the end insulation only and is greater than without initial compression. Eqns. (10) and (11) can be modified easily to take into account the effect of initial compression.

Two difficulties arise in applying this idea in practice. First, an initial stress of half the crushing stress is large, possibly too large to be practicable, and secondly, insulation under constant stress is subject to creep, which raises practical difficulties in maintaining the stress.

Mr. W. Casson: Although short-circuit levels have increased considerably of recent years, so has the size of transformers. There can be few cases in which short-circuit currents through a transformer exceed 7·4 times full-load. The author states that dead short-circuits on a modern well-run system are rare. I do now know whether the Grid comes in that category, but it is surprising how many dead short-circuits occur owing to circuits

being switched in with safety earths still connected. In this respect surely the worst fault condition for mechanical forces is when the doubling effect occurs in a transformer when switched in on one winding with the voltage of one phase at zero and with a short-circuit on the other winding.

Auto-reclosing is not employed at present on the 132 kV and 275 kV systems of the C.E.A., and single-phase fault throwing at 132 kV only imposes through currents on the associated transformer never exceeding 5 times full-load.

There seem to be conflicting statements in the paper regarding the effect of duration of fault. The only way of checking the behaviour of transformer system faults is an internal inspection. I suggest that, instead of recording the actual short-circuits in service, an indicating device consisting of a number of simple attracted-armature relays with counters should be provided, one set to operate at, say, 8 times and the other at 6 times full-load. This would be a very simple way of providing information on short-circuits likely to be detrimental to the transformer. I suggest that up to a certain size it is possible to obtain the same current from a test source as would be obtained from a supply system of zero impedance by energizing the transformer at a voltage higher than normal.

I do not think it would be satisfactory for the purchaser to specify the supply system conditions for which the transformer is to be used initially. This would mean tailor-making every transformer. On the C.E.A. system a transformer might be moved several times during its life.

Mr. E. C. Rippon: The author's concepts of mechanical strength categories (Section 8) are a valuable contribution to the design of transformers.

The importance of using materials with a low compressibility in windings has been appreciated for some time, and I have previously given information on this subject which was published in the discussion of Reference 16.

The author is quite right to draw attention to the increase in the number of faults now possible on transformers in modern systems, but I feel that he has overstated his case. Even so, the greatest number will be phase-to-earth and not 3-phase faults, so that in this respect the 3-phase short-circuit type test usually specified is unrealistic on still another score. I agree with the author that 3-phase short-circuit tests can only be made on transformers of moderate rating in view of the limited 3-phase output of existing switchgear proving stations. I would, however, point out that the output of the proving stations can be very materially increased if tests are made single-phase. Such tests would be representative of service conditions and could be made on transformers of very high rating. Single-phase short-circuit tests should be feasible on transformers exceeding 200 MVA output, and the duration of the fault, dependent upon the parameters of the test circuit, might be limited to periods of the order of 10 cycles.

I do not see any objections to single-phase tests and I should like the author's opinion on this proposal.

If large transformers can be tested for short-circuit in this modified manner, the number of short-circuits to be applied requires reconsideration. I agree with the author's proposals in this respect. One remaining problem is the interpretation of the test. Are engineers convinced that it is possible to state categorically that a transformer has suffered no damage after a series of short-circuit tests, since it is generally impracticable to examine the inner winding, which is usually the most highly stressed? What criteria of acceptance would the author suggest?

Mr. G. B. Harper: Service records indicate that more than one type of large transformer manufactured in the early 'thirties and before was inferior mechanically by comparison with modern construction, but it should be recorded that practical experience gained with these early designs has apparently been put to good effect.

In an attempt to relate the mechanical strength of transformers to present-day service experience, a survey has been made of major breakdowns experienced on the C.E.A. 132 kV transmission system during the past nine years. The term 'major breakdown' in this context defines a fault which involves return of the transformer for repair. Over this period, out of a total of 39 breakdowns, seven could be directly attributed to mechanical failure, of which six involved transformers manufactured before 1936 and were all associated with designs known to be mechanically weak. The remaining one involved a defect which was associated with special circumstances not likely to apply to an average case. Of the remaining incidents, the possibility of mechanical weakness contributing to the breakdown can be ascribed to only three cases, and even for these the available evidence suggests the possibility of other factors being mainly responsible.

Putting these facts into perspective, average total major breakdowns per annum represent one for every 105 transformers installed, and those due to mechanical weaknesses, both known and suspected, one for every 450, of which over 40% of the units are over 20 years old. It should be emphasized that the total of 39 breakdowns refers to transformers returned to the makers' works for all causes; and as a measure of reliability, the average non-availability of transformer capacity taken over a 6-year period, 1949–55, taking into account all faults which involved tripping of the transformer, assessed on an outage-duration basis, is 0·47% of the total transformer-hours available per annum.

A survey has also been made of general system faults over the last eight years, 1948–56, and a summary made of incidents

Table A

Major Transformer Breakdowns: C.E.A. 132 kV Transmission System

	Date of manufacture	1948 –1949	1949 –1950	1950 –1951	1951 –1952	1952 –1953	1953 –1954	1954 –1955	1955 –1956	1956 –1957	Total
Total major breakdowns investigated	Pre-1936	7	—	5	2	—	—	—	3	1	18
	Post-1936	—	2	2	1	2	2	7	2	3	21
Breakdowns due to short-circuit forces	Pre-1936*	3	—	1	1	—	—	—	—	1	6
	Post-1936	—	—	—	—	—	—	—	—	1	1
Breakdowns which might have been caused by short-circuit forces	Pre-1936	—	—	1	—	—	—	—	—	—	1
	Post-1936	—	—	—	—	—	—	—	1	1	2
Major breakdown, percentage of transformers installed		1·8	0·5	1·6	0·6	0·4	0·4	1·2	0·9	—	Average 0·9

* All attributable to known or suspected weaknesses.

which could have conceivably resulted in short-circuit forces in the transformers. These have been tabulated to show to some extent the degree of severity; i.e. faults occurring in the substation in general should give rise to more severe conditions than those occurring on an overhead line remote from the substation.

Taking 132 kV overhead-line faults, the survey shows a yearly average of approximately one fault per five transformers installed, whereas substation faults involve one fault per 10 transformers installed. The latter figure compares with the lower limit quoted by the author in Section 11, but even considering these it is suggested that only a small percentage would represent a severe short-circuit on the transformer. It must also be appreciated that one system fault would generally result in short-circuit forces being imposed on more than one transformer.

In Section 12 the author proposes that a minimum external impedance should be specified by the purchaser and the resultant short-circuit rating marked on the rating plate. Whilst such a step may show theoretical advantage, the general application is impracticable. Two approaches to the problem can be made: either the system can be planned on the basis of the natural impedance values normally obtained, or definite impedance values can be specified by the purchaser to suit his system conditions. The latter approach could upset the large measure of standardization achieved, involving unnecessary complications and limitations for both the manufacturer and the user.

Mr. G. N. Leech: I am surprised to learn from the author that short-circuit stresses in normal power transformers have in the past been a frequent cause of trouble: my own company's experience has been to the contrary.

I should like, therefore, to refer to some aspects of the subject which may help to clarify the overall picture.

Table B

MAXIMUM ATTAINABLE THROUGHPUTS

(i) System nominal voltage, kV	132			275		
(ii) Transformer continuous rating, MVA	30	60	90	120	180	240
(iii) Maximum throughput on short-circuit, MVA	275	510	710	720	1030	1300
(iv) Ratio of (iii) to (ii) ..	9·2	8·5	7·9	6·0	5·7	5·4

It would appear that for any large power system, the symmetrical r.m.s. fault current is unlikely to exceed about 15 kA under the worst conditions. If the 'natural' impedances of 50 c/s 3-phase transformers are taken as 10% at 132 kV and 15% at 275 kV, Table B is derived.

The values of 'over-current ratio' in line (iv) do not seem to be unduly onerous, and I would expect that what might be described as a normal commercial design of transformer would remain undamaged by a reasonable number of through faults of the magnitude indicated. Even when much lower transformer impedances, such as 6%, are specified for use in conjunction with long transmission lines abroad, the over-current ratios are still low, and the transformers should give entirely satisfactory service.

In Section 12, the author mentions that in connection with the design of generator transformers it may be permissible to include the generator impedance in assessing the ability of the transformer to withstand the effects of fault conditions. This may be true when considering faults on the high-voltage system, but it is to be assumed that no manufacturer of repute would design a generator transformer which was incapable of withstanding the effects of a fault on the generator.

Mr. E. J. Whitcher: The author suggests that we should ease the requirements on the short-circuit strength by specifying the external impedance of the system on which they are to be used. It so happens that the London Electricity Board does just that, but not for reasons of mechanical strength. The high reactances of the transformers commonly used to-day are the major reactances in the system. Therefore system short-circuits closely approximate to dead short-circuits on the transformers, and on this account the L.E.B. would not wish to use specifications less severe than the national standards.

Experience in the L.E.B. with transformers, admittedly nearly all of smaller sizes than those mentioned in the paper, may be summarized as follows. Faults on the low-voltage system occur at the rate of about two a day, and each of these affects a small number of transformers out of a total on the system of about 10 000. The number of transformer failures, among 2 000–3 000 of the above transformers installed during the last nine years, totals seven.

Among the bigger transformers (10–15 MVA) about 180 through faults per annum are shared by about 120 pairs of transformers. The number of failures among these transformers averages about one per annum if auxiliary equipment is excluded. Experiences with a group of 66/33 kV and 33/11 kV transformers are given in Table C.

This is typical of the evidence available to the supply engineer who has to decide what action to take whenever new knowledge and new theories are presented in a paper of this kind. I would like to ask the author, on this evidence, what should I do?

Additionally, when considering alternative system layouts, especially where control of short-circuit is an important factor, one is often faced with the choice between one large unit and two smaller units of half-capacity. Would the author consider that the relatively better mechanical strength of the smaller units is a significant advantage within the range of sizes from, say, 15 MVA to 60 MVA?

Mr. R. M. Charley: I also should like to advocate the adoption of 3-phase transformers. The contract for the first transformers ordered by the Central Electricity Board in about 1928 was shared between the author's company and that with which I am concerned: they were 3-phase units. At about the same time another contract was placed for banks of single-phase units.

To-day 210 MVA and 345 MVA 3-phase generator-transformers are being built, without any qualms about short-circuit forces.

Table C

LIVES OF 66/33 kV AND 33/11 kV TRANSFORMERS

Size of unit	No. in group	Impedance	Earthing	No. of through faults	Period	Evidence of deterioration
MVA		%			years	
50	3	10	Resistance	10	20	None
12	4	12	Solid	36	16	None
12	4	8	Resistance	122	30	None

The illustrations in the paper show disc-type windings, and while it is true that the paper is somewhat academic, with very practical applications, there must surely be some significance in the fact that the author decided that disc-type windings were best. I agree with this, especially when one other factor is considered. Transformers have to be built not only to be safe under short-circuit conditions causing mechanical forces, but also to have adequate impulse strength, and the two features are very closely associated.

Another type of transformer has a winding which I think is commonly called the 'barrel' type. Admittedly it is good from the point of view of impulse characteristics, but mechanically it is weak. At any rate, it is by no means equivalent to the disc-type winding, especially when a particular type of winding arrangement is used.

Such a winding is uniform throughout; hence there is no dissymmetry between high- and low-voltage windings. Thus one of the most serious factors involved in connection with mechanical strength is eliminated, or at any rate greatly reduced.

It would seem that the only limitation to building the larger transformers is that of transport. I earnestly hope that transport authorities will increase their efforts to enable heavier weights to be transported than are possible at present.

Mr. J. Solomon (*communicated*): I should like to ask whether the analysis and conclusions reached by the author are applicable to the shell type of construction, as well as to the core type? If this is not the case, perhaps some identification might be given in the title of any such restrictions in the application of the paper.

Would the author also please give some general comparative guidance in dealing with the two types, in respect of their mechanical strengths?

Mr. W. N. Waggott (*communicated*): I should like to refer to Table 3, recording failures in service of certain transformers of 1929 design a few years after commissioning, since I was responsible for the ordering of these transformers and the approval of the designs. I was also concerned in the subsequent investigations following the breakdowns and the decisions taken regarding rebuilding.

The transformers were at the time unique. They were for 132 kV working with on-load tap-changing, were among the earliest of their voltage and rating to be built as 3-phase units, and were restricted to dimensions and weights suited to the available transport facilities. Moreover, competition in the field of transformer manufacture was then acute and prices were low. These factors, coupled to the state at that time of the art of transformer design and manufacture, each played their part towards subsequent events, and must be carefully and impartially reviewed along with other circumstances, such as the exceptional operating conditions referred to by the author.

Other transformers withstood the same operating conditions. Moreover, at that time system conditions were such that prospective short-circuit duties could not have been severe.

In the light of the above considerations, it would be imprudent to draw conclusions from the failures in question. These could indicate no more than that the particular transformers fell short of their expected performance.

[The author's reply to the above discussion will be found on the next page.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 11TH MARCH, 1957

Mr. F. C. Winfield: System design is inevitably a continuous effort to secure maximum total economy, which means minimum capital plus annual costs. In considering, therefore, whether we ought to add new restrictions or requirements to transformers materially affecting capital costs, we have to decide whether the actual record to date shows that we are experiencing an unacceptable rate of failure, i.e. annual costs. In this respect the paper is a little weak, in that the actual experience quoted is not adequate to allow good judgment of this factor.

If an examination of the life-years of high-voltage transformers on the national Grid reveals real trouble existing or to be expected with increase in size, we must first take present action to control fault MVA, auto-reclosing, fault throwing or the transformers themselves in our immediate developments, and long-term action to improve design.

(i) The system designer already does his best to control fault MVA, and it is unlikely that materially more can be done economically.

(ii) It would not be a very serious matter in Great Britain if we had to abandon auto-reclosing and fault throwing.

(iii) Whilst a nuisance, it would not be a very expensive matter in relation to total system costs if we had to restrict transformers in size to, say, 100 MVA 3-phase or equivalent.

I might comment here that the author's suggestion of mechanical supports between coils is really the limiting case of internal division of transformers as opposed to external division. One can well imagine supports dividing transformer windings internally into, say, four parts so far as the electromagnetic forces are affected.

Long-term action must envisage advance in design based primarily on sample and model testing.

Mr. R. R. Pattinson: Increased system loading allied to bigger transmission distances is resulting in higher system voltages. The added insulation required on transformers to withstand the consequent higher impulse and switching over-voltages, together with the use of higher current densities in the windings, makes the modern transformer more susceptible than hitherto to short-circuits. It is opportune, therefore, that the author should ask the question implicit in his paper of whether transformers are to continue to be purchased as a commercial risk or as a tested reality.

Doubt has been expressed on the reliability of the formulae, so let us examine the alternative of testing. Full-scale tests could be either routine or type. Routine tests are impracticable, as the transformer after test should be dismantled to ascertain if it has sustained damage, since the inner windings tend to suffer the greatest damage. In this country there are about 20 manufacturers of whom several are capable of producing annually transformers of total capacity up to 6 million kVA. These transformers are destined for service in many parts of the world; thus the number of different types must be quite large. If, in addition, the short-circuit tests are to be repeated as often as 10 times it is doubtful if the existing short-circuit testing stations could cope. Even if all transformers below 132 kV were to be disregarded and the assumption made that the largest transformers are beyond the capacity of the test plants, that doubt must still remain. Selective tests, therefore, appear all that can be contemplated, and this seems to agree with the conclusion reached by the International Electrotechnical Commission and the British Standards Institution.

However, there may be other and more practicable lines of approach. Waters has shown that the highest individual stresses occur at the ends of a winding, and I wonder if this fact does not open the way to testing 'truncated' full-scale models from which those sections of windings with balanced ampere-turns and associated core have been eliminated. It might be found that the

results of such tests could be extrapolated for the bigger units, or even demonstrate that full-scale models are unnecessary and that miniatures could be introduced. Admittedly, it would be necessary to correlate the test results with what would have occurred on the complete transformer, but the complications of doing this might be of a minor order. I should be interested to have the author's views.

[The author's reply to the above discussion will be found below.]

NORTH-WESTERN CENTRE SUPPLY GROUP, AT MANCHESTER, 10TH APRIL, 1957

Mr. L. C. Richards: I do not think the method of supporting each winding section, mentioned in Section 11.3 and Fig. 16, is very practicable for large transformers. It was tried some 25 years ago, but is expensive both in respect of materials and losses. In the light of present design practice it can hardly be regarded as a necessary requirement.

I agree with the author that the circuit impedance should be taken into account when designing the transformer. This does not necessarily mean an individual assessment of impedance for each transformer, but rather the determination of one figure for the whole system, so that a transformer can be located at any desired point on that system.

It is agreed that short-circuit stresses are to some extent cumulative. In this connection the author suggests the possible application of 10 short-circuits followed by dismantling and examination of the windings, but this could be a very expensive exercise and would not normally be regarded as necessary.

Mr. E. W. Connon: Looking at the work from the point of view of the design of electricity supply systems, it should be appreciated that a transformer has functions other than the primary one of changing the system voltage. It has, in addition, the equally important job of limiting the short-circuit levels to within practicable limits. Thus the short-circuit performance of the transformer is equally important as that of the circuit-breaker.

In spite of a great deal of research work, we are still a long way from being able to give transformers a genuine proved short-circuit rating.

This paper, however, brings us much nearer to this position; in fact, the author has been able to establish a coherent relationship between short-circuit stress and transformer life. We have also seen elsewhere relationships stated between transformer overload and transformer life, and presumably overloading will also reduce the short-circuit life. Perhaps the author could enlarge on this aspect.

The author suggests in Conclusion (*d*) that recording of short-circuits will enable remaining expectation of life to be assessed. This is a very great step forward, but while automatic fault-recording equipment is, of course, available, it is by no means as yet free from troubles, and in addition is somewhat expensive. For this reason I was attracted by the description (Section 11.1) of means whereby the impending mechanical failure of Cases L and M was forecast by electrical measurement of winding displacement. If such arrangements could be more fully developed we would have a considerably more direct method of dealing with this matter. Indeed, the fact that, in the instance mentioned, rectification was possible before failure occurred, is of value because it avoided, not only damage to the transformer itself, but also risks of failure of supply.

Mr. H. G. Montgomery: Mr. Norris has introduced for the first time a theory which attempts to correlate the calculated short-circuit forces and the short-circuit behaviour of the transformer in service. Some very valuable information is given in support of the theory.

The paper is most opportune because, although the 200 MVA transformers of to-day are not unduly restricted in design by force considerations, transformers of 350 MVA and above may be.

The cumulative and possibly critical nature of the strains indicates the necessity for constantly reviewing the stress/strain relationship for conductor and insulating materials. I think such investigation should be carried out under combined axial and radial loading, preferably in oil. The opposing inertia and damping forces of the oil are very large. I think that more attention should be paid to the time factor in any investigation of conductor materials. The reason for this is indicated in the following remarks on auto-reclosing.

It is possible that the practice of auto-reclosing is not as serious as the paper would indicate because the work hardening produced by the first application of the fault may be instantaneous, whereas the annealing, due to temperature rise, may have a definite time lag. It is therefore likely that two short-circuits following each other are not as serious as the same two short-circuits separated by a long period.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. E. T. Norris (*in reply*): I agree with all Sir John Hacking's remarks.

The egg analogy is, I think, correct if one substitutes number of short-circuits for time. Just as each microsecond the egg will be increasingly nearer upset, so each short-circuit the transformer, when the critical stress K_c is reached, will be increasingly nearer collapse.

The cumulative effect of short-circuits developed in the paper implies that most failures will occur in the older transformers with long service. Since these transformers were necessarily of equally old design several speakers have assumed that transformers of modern design will be less vulnerable.

This is an unsafe corollary. The basic mechanical structure of transformer windings has changed little over the last 30 years. Section 9.1 and Table 1 of the paper could have been included complete in a paper written 30 years ago.

The main improvement in design is possibly a better electromagnetic balance of the windings, i.e. lower values of d_0 in the design stage. Fig. 9, however, shows that whilst this improves the initial short-circuit strength K_0 it does not greatly affect the expectation of life K_1. When the design dissymmetry was removed completely from transformers A–C of Table 3, the life increased only from 6·5 to 16 short-circuits as shown in Case D. It needed a reconstruction with better materials from Table 1 to give the safe result of Case E.

A rough estimate of the life of any particular size and design of transformer can be quickly obtained by considering the critical strength only. Eqn. (11) shows that this is dependent chiefly on the insulation characteristic c of Table 1, since p is determined by other design requirements and t by the necessary insulation values.

Section 10 of the paper shows that three assumptions were necessary for the derivation of expectation of life. These are as follows:

(i) Values of c from Table 1. This is possibly an over-simplification in view of the complex stress/strain relations of

insulation, as shown in Section 9.1 and Fig. 6, and the effect of insulation ageing mentioned by Mr. Connon.

(ii) An average initial dissymmetry d_0 of $0 \cdot 5\%$ (apart from design values). It was then found that to obtain the agreement with service experience shown in Fig. 15 it was necessary to assume

(iii) A factor 9 for the number of nominal short-circuits corresponding to one effective fully asymmetrical short-circuit on the transformer. This is a plausible value and includes a component of nearly 3 because most faults are single-phase, as pointed out by Mr. Rippon.

Whilst this combination of assumptions gives excellent results it does not follow that they are necessarily correct individually. It is, in fact, unlikely. I feel that if the concepts introduced in the paper are accepted there is room for much further study of the mechanical characteristics of insulation and of the conductors, whether copper or aluminium.

The service life in years of a transformer depends externally on the number of faults per transformer per annum.

This is a service record not usually obtainable, and Messrs. Harper and Whitcher have given some very useful information. Compared with a range of 0·1–1·0 given in Section 11 and a value of 0·52 from Fig. 14, Mr. Harper quotes 0·1 for station faults and 0·2 for line faults. Mr. Whitcher finds 0·67 for transformers of 10–15 MVA (which are not generally very vulnerable) and 0·17 for a limited experience of 50 MVA units.

Mr. Waters's suggestions for external clamping of the windings are complicated not only by the difficulties he mentions but also by the different compressibilities of two windings usually of high- and low-voltage insulation, respectively, and by resilience and follow-up characteristics of the clamps. Moreover, in practice, winding dissymmetries are generally more complex than is assumed in Fig. A, and even the forces on the two windings are not equal, as Mr. Waters has shown in Reference 12.

The effect of magnetizing current when closing on to a dead short-circuit, mentioned by Messrs. Richards and Casson, can, if desired, be considered by suitable increase in K_s in the formulae.

I agree with Mr. Rippon concerning single-phase tests and also that, as stated in Section 12, complete dismantling for examination is necessary after a short-circuit test.

In reply to Mr. Leech, the short-circuit currents of many large power systems are much greater than 15 kA, though possibly not in this country.

Mr. Whitcher will find no general advantage in using small units, at any rate up to 60 MVA. The reasons for this are given in conclusion (vii) of Section 9.3. The position is very different when one comes to consider 200–600 MVA units, and here individual study is vital.

Disc-type windings were assumed for the reasons given in Section 4 and not, as Mr. Charley suggests, on grounds of possible mechanical or other superiority.

In reply to Mr. Solomon, the method of analysis developed in the paper is equally applicable to the shell-type construction, as explained in Section 3.

I cannot agree with Mr. Waggott that it is imprudent to draw conclusions from the failures in Table 3 when these conclusions so consistently check theory and calculations over a wide range of conditions as summarized in (*a*)–(*h*) of Section 11.1.

The interesting suggestion of Mr. Pattinson requires more detailed study than is possible here. The crushing strength of the windings can, of course, be measured directly, and this has been described in Section 9.2, but the crushing stress depends on the progressive compression of the insulation, which cannot easily be segregated into balanced and unbalanced components.

620.197.5

Paper No. 2336
Feb. 1957

CATHODIC PROTECTION

By L. B. HOBGEN, O.B.E., M.I.Mech.E., Member, K. A. SPENCER, B.Sc.Tech., and P. W. HESELGRAVE, B.Sc.

(*The paper was first received* 2*nd November*, 1956, *and in revised form* 10*th January*, 1957. *It was published in February*, 1957, *and was read before the* EAST ANGLIAN SUB-CENTRE 5*th March*, *and* THE INSTITUTION 7*th March*, 1957.)

SUMMARY

The paper deals with the theory and practice of the method of corrosion mitigation known as cathodic protection. The nature of electrochemical corrosion and the fundamentals of cathodic protection are briefly discussed. This is followed by a survey of the two practical methods of achieving cathodic protection—sacrificial anodes and power-impressed currents. Since the method of measuring potentials is not that of normal electrical practice, the subject is considered in some detail together with the method of measuring soil resistivity. The possibility of adversely affecting other buried services is noted, and current practice in carrying out potential tests with the owners of such services, and of bonding to eliminate adverse effects, is considered. Finally the application of cathodic protection and the general economics affecting its use are discussed.

(1) INTRODUCTION

The present age is one of metals, and of those in use iron is by far the most important. The tonnage of iron and steel produced greatly exceeds that of all other metals. Unfortunately, iron readily combines with the oxygen of the atmosphere or of solutions in which it is immersed, and in doing so it reverts to one of the states in which it may be found naturally. Such reversion to a state of the oxide, carbonate or other compound is called corrosion, and the paper is concerned with a specific method of preventing the corrosion of metals, principally iron or steel, which would occur when they are immersed in an aqueous solution. The method is not new; it was known and used as far back as 1824, when Sir Humphry Davy presented a paper to the Royal Society dealing with the use of iron anodes to protect the copper sheathing of naval vessels.

The use of cathodic protection has increased greatly in the last three decades. This has been occasioned principally by the phenomenal growth in the mileage of buried mild-steel pipe lines for the transport of oil, oil products and natural gas, and by the greater use of steel piles for jetties over this period. A better understanding of the principles of protection and the accumulation of evidence proving its economic value have also assisted in making the method more generally applied.

Before the mechanism of cathodic protection could be established and the conditions under which it would be effective could be determined, considerable experimental work was needed to establish the electrochemical nature of corrosion occurring in aqueous solutions. It is necessary to understand the theory that was evolved in order to understand why cathodic protection is effective, and a brief résumé of the relevant facts is provided.

(2) MECHANISM OF ELECTROLYTIC CORROSION

(2.1) The Corrosion Cell

The tendency of a metal to lose positive ions to an electrolyte in which it is immersed results in the parent body acquiring a negative charge; an equilibrium potential is established between the metal and electrolyte at which the rate of loss of ions from the surface is equal to the rate at which they are drawn back by this negative potential. This potential depends upon the nature of the metal and its surface, and the nature and concentration of ions in the electrolyte.

When a metal is immersed in a normal concentration of its own ions it reaches a potential which determines its place in the electromotive series. This series is a list of the metals arranged in order of the magnitude and polarity of their potentials. The potentials quoted are usually referred to a hydrogen electrode, and they range from $-3\cdot02$ volts for lithium to $+1\cdot42$ volts for gold. However, the series must be used with reservation when applied to corrosion problems, because the presence of surface films, and the fact that metals are never used in solutions containing large concentrations of their own ions, means that the potentials are considerably modified in practice, and in certain circumstances the order of two metals in the series may be reversed.

When two areas of a continuous metallic structure have different equilibrium potentials there is a resultant e.m.f. equal to the algebraic sum of the two interface potentials and the junction potential between the two areas of metal, tending to cause the flow of an electric current round the circuit formed by the metal and the electrolyte. The areas of metal surface from which positive ions leave to enter the electrolyte are known as anodes, and those to which positive ions are attracted are known as cathodes. Since there is not normally a large concentration of the parent metal ions at the cathode the transfer of charges across the cathode-electrolyte interface must take place by some mechanism other than the simple plating of metal ions. Two possible cathode reactions are as follows: First, when oxygen is present it is absorbed and electrons are transferred by the reaction

$$2H_2O + O_2 + 4e = 4OH^- \quad . \quad . \quad . \quad (1)$$

Secondly, when oxygen is absent and the electrolyte is neutral or near neutral in respect of acidity, a reaction enabling charges to be transferred across the cathode surface cannot occur at an appreciable rate, and, owing to the presence of a layer of hydrogen which is built up at the cathode surface, corrosion virtually ceases.

When the electrolyte is acid, the concentration of hydrogen ions is high and charges are transferred by the reaction

$$2H^+ + 2OH^- + 2e = H_2 + 2OH^- \quad . \quad . \quad . \quad (2)$$

In both reactions the liquid near the cathode surface becomes more alkaline, and in reaction (2) hydrogen gas is evolved at the cathode.

A corrosion cell may be represented by a simple equivalent circuit (see Fig. 1). I_0 is the corrosion current, and the loss of metal from the anode will be proportional to the total electric charge flowing from the surface.

(2.2) Types of Corrosion

Virtually all corrosion of metals immersed in an electrically conducting medium is effected by the foregoing mechanism.

Mr. Hobgen is with the Air Ministry.
Mr. Spencer and Mr. Heselgrave are with Spencer and Partners.

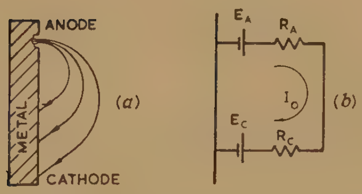


Fig. 1.—Equivalent circuit of corrosion cell.

(*a*) Corrosion cell. (*b*) Equivalent circuit.

However, it is convenient, in practice, to distinguish between the various factors which cause potentials to be developed and between the factors which cause accelerated rates of corrosion by reducing the circuit resistance. The following terms are in common use:

(*a*) *Galvanic Corrosion.*—Occurs when different metals are electrically connected and immersed in an electrolyte. The same type of corrosion also occurs if part of the same metal contains inclusions, has been stressed or retains part of a coating such as millscale.

(*b*) *Concentration Cell Corrosion.*—Caused by differing concentrations of soluble salts in the electrolyte at various parts of the same metal. Apart from soluble salts, differing concentrations of oxygen have a similar effect.

(*c*) *Stray Current Corrosion.*—Caused by direct current flowing from metal to an electrolyte.

(*d*) *Bacterial Corrosion.*—Occurs in anaerobic water-logged soils where sulphate-reducing bacteria have the ability of removing hydrogen from cathodic surfaces. This reduces the resistance of the circuit, allowing increased current to flow and increasing corrosion at the anodes. The bacteria also produce hydrogen sulphide, which causes corrosion.

(3) PRINCIPLE OF CATHODIC PROTECTION

Since corrosion is the loss of positive metal ions from the metal surface it follows that, if positive current is caused to flow to all parts of the surface from an external source, corrosion cannot occur.[1] This is the principle of cathodic protection. The external sources which are used for this purpose are discussed in Sections 5.1 and 5.2.

The equivalent circuit of a corroding cell to which protective currents are flowing will be as seen in Fig. 2, whence

$$E_A - E_C = I_1 R_A + R_C(I_1 + I_2)$$

$$I_1 = \frac{E_A - (E_C + R_C I_2)}{R_A + R_C}$$

where E_A = Open-circuit potential of the anode.
E_C = Open-circuit potential of the cathode.
R_A = Effective anode resistance.
R_C = Effective cathode resistance.
I_0 = Corrosion current.
I_1 = Current from the anodic area.
I_2 = Current from the external anode.

For corrosion to cease I_1 must be zero.

Therefore $$(E_C + R_C I_2) = E_A$$

This means that sufficient current must flow through R_C for the total voltage drop at the cathode to equal the open-circuit voltage of the anode.

The principal difficulties in applying this criterion lie in determining the open-circuit potential of the anode and deciding which part of the physical circuit comprises R_C.

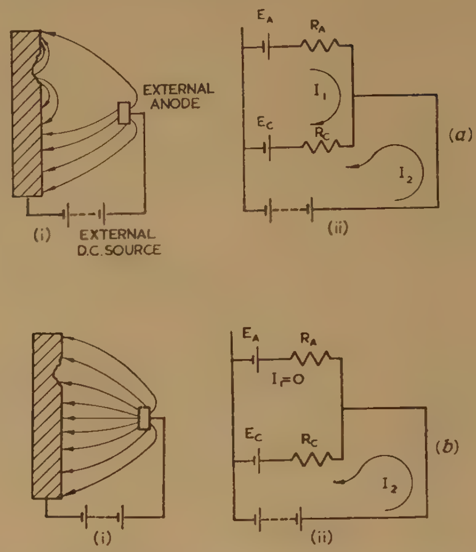


Fig. 2.—Equivalent circuits of cathodically protected metal.

(*a*) Partial protection $I_1 > 0$.
(i) Physical circuit.
(ii) Equivalent circuit.
(*b*) Complete protection $I_1 = 0$.
(i) Physical circuit.
(ii) Equivalent circuit.

(4) FACTORS AFFECTING THE APPLICATION OF CATHODIC PROTECTION

(4.1) Current Requirements

The current which flows to the surface when the potential depression is sufficient for protection varies enormously with conditions. It has already been stated that, in solutions containing dissolved oxygen, the principal cathodic reaction is the reduction of oxygen to hydroxyl ion; this is equally true whether the metal is corroding naturally or whether the currents are being caused to flow for the purposes of cathodic protection. The reduction to hydroxyl ions involves the transfer of electrons from the metal to the solution, and hence the rate at which this reaction occurs determines the rate at which electrons must flow from the anode via the metallic circuit to the protected structure, i.e. it determines the current required for protection. The rate of arrival of oxygen at the interface is controlled principally by two factors: first, the concentration of oxygen in the electrolyte, and secondly, the thickness of the diffusion layer. The range of currents required for protection is considerable—1–5 mA/ft^2 for bare steel in sluggish water containing small amounts of oxygen, 20–100 mA/ft^2 for steel in highly-aerated rapidly-moving solutions, and 0·1–5 mA/ft^2 for bare steel in soil.

When the electrolyte is strongly acidic it is still possible to protect ferrous surfaces, but since the hydrogen-ion concentration is high, these ions are readily discharged, considerable amounts of gas are evolved at the protected surface and the current required for protection is high—1 amp/ft^2 or more for concentrated acids such as are used in plating baths.

(4.2) Cathodic Effects

The build-up of alkali at the cathodic surface has two effects which may be beneficial or deleterious depending on the metal being protected. The increasing pH-value of the electrolyte adjacent to the cathode makes the formation on the metal surface of a relatively insoluble film of hydroxide more probable, and this helps to reduce the corrosion in the case of iron and steel. Alkali may attack surface layers which would otherwise protect

aluminium. Thus, when this metal is to be protected, care must be taken that only the minimum current required for protection flows; if the current is excessive the cathodic alkali attacks the protective surface film with the formation of aluminates, and the metal may become pitted. A similar effect may occur with lead. If the metal to be protected is coated with natural oil-base paint, the coating may be softened and damaged by the action of the alkali. When a steel surface, which is to be cathodically protected, is painted, a synthetic rubber, bituminous or other material not attacked by alkali should be used. If the current density is high, appreciable amounts of hydrogen will be evolved from the protected surface, and this may cause the disruption and blistering of coatings.

One further cathodic effect of note is that encountered in certain waters containing magnesium and calcium ions, when relatively insoluble films of their salts are formed on the metal surface owing to the lower solubility of these salts in the alkaline solution at the cathodic surface. The presence of such layers is beneficial, as it reduces the current required for protection of structures such as jetties, but it is unwelcome in heat exchangers in that the deposits may appreciably reduce heat transfer rates.

The foregoing factors indicate the care required in applying cathodic protection. Despite these limitations, however, iron, steel, lead and aluminium surfaces have all been successfully protected.

(4.3) Current Distribution

The presence of a coating of high electrical resistance at the metal–electrolyte interface not only decreases the total current required for protection, but also improves the distribution of current to the surface. The current flowing along any path to the surface of the structure will be proportional to the electrical resistance of that path, and if a large part of this resistance occurs at the surface, the potential there will be the more uniform.

A pipe line or cable which is extremely well coated may be regarded as a single-wire transmission line with an earth return, and the distribution of potential along it produced by current flowing from a single remote ground-bed may be calculated from the equation given below; the type of curve on this theoretical basis is shown in Fig. 3. However, the potentials obtained in

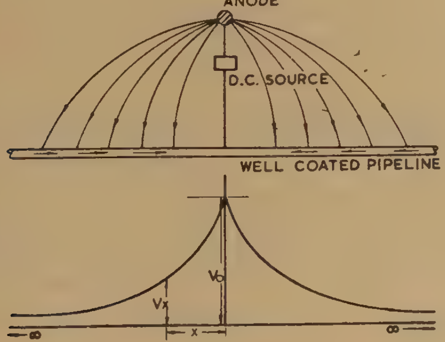


Fig. 3.—Diagrammatic curve showing distribution of potential along a coated pipe line.

practice do not normally lie on a smooth curve, so that the utility of this method of calculation is limited.

$$V_x = V_0 \varepsilon^{-(RG)^{\frac{1}{2}}x}$$

where V_0 = Pipe-soil potential change at the 'drainage point,' volts.

V_x = Pipe-soil potential change at a distance x from the 'drainage point,' volts.

R = Resistance of the pipe line, ohms per 1 000 ft.

G = Conductance to earth of the pipe line, mhos per 1 000 ft.

x = Distance of the point considered from the 'drainage point', ft $\times 10^3$.

In order to obtain a coating of the highest quality, it is necessary that the initial operation be carried out with extreme care and that flaws in the coating be detected and repaired. The inspection of the coating for pinholes may readily be carried out with a high-voltage source and a spring-type electrode.

When this procedure has been adopted it is possible to protect up to 50 miles from one source of direct current. With bare pipe the economical spread from a single current source is of the order of one mile.

(5) PRACTICAL METHODS OF APPLYING CATHODIC PROTECTION

There are two means of applying cathodic protection; they are known as the 'sacrificial anode' and the 'power impressed' methods. The equipment required for each method is different, and it is convenient to discuss them separately.

(5.1) Sacrificial-Anode Method

Cathodic protection by sacrificial anodes can be effected by attaching to the structure blocks of metal which are more electro-negative than the metal of the structure and immersing them in the common electrolyte. The metals used are magnesium, zinc and aluminium.

The metal of a sacrificial anode readily loses positive ions to the electrolyte and consequently acquires a surplus of electrons, some of which flow via the metallic circuit to the protected structure. This depresses the structure potential and causes the metal-electrolyte reaction to be such that positive ions do not leave its surface, i.e. the metal is cathodically protected. The type of installation is shown in Fig. 4.

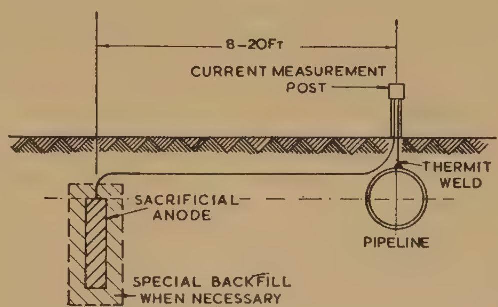


Fig. 4.—Sacrificial-anode installation.

The metal of the anode must be sufficiently electro-negative to the protected metal for an appreciable current to flow. Hence an important factor is the 'effective driving voltage', i.e. the potential difference between the anode and structure when the latter is polarized to a protective level. Typical values of this quantity for magnesium and zinc anodes immersed in soil and protecting mild steel are given in Table 1.

The theoretical value of electrical charge which can be obtained from a given anode may be computed, but the practical value will fall short of this figure because the anode undergoes self-corrosion owing to inhomogeneity of its surface, i.e. current will flow from one part of the anode surface to another. Thus the anode would still corrode at an appreciable rate even if it delivered no external current.

The percentage anode efficiency is defined as

$$\frac{\text{Actual charge per pound}}{\text{Theoretical charge per pound}} \times 100$$

and typical values for magnesium and zinc are given in Table 1.

The figures in Table 1 are typical for applications in soil and sea water, and are only given to indicate the approximate values

Table 1

DATA ON GALVANIC ANODES

	Mg	Zn
Effective driving voltage*	0·85	0·25
Theoretical charge per pound, Ah ..	1 000	372
Actual charge per pound, Ah ..	200–500	335
Anode efficiency	20–50%	90%

* Against mild steel depressed 0·85 volts with reference to a copper half-cell (which will be described later).

to be anticipated. It will be seen that magnesium has a driving voltage more than three times as great as zinc, and is therefore preferable to zinc in applications where the resistance of the electrolyte is not extremely low. Zinc has a high anode efficiency, and consequently when the electrolyte resistance is sufficiently low, e.g. in sea water (20–30 ohm-cm), it may be preferable.

'Magnesium' anodes are usually fabricated from a magnesium-aluminium-zinc alloy, since this has been found to corrode more evenly than the pure metal. Zinc anodes are made of the pure metal and should contain preferably less than 0·01% impurity.

Most of the techniques developed for the use of sacrificial anodes have been associated with their applications to ferrous structures immersed in soils and sea water. When iron or steel is to be protected in other aqueous solutions, especially when the temperature is enhanced, simple tests should be carried out with the 'sacrificial metal' in question in order to ensure that the driving voltage is positive and of sufficient magnitude. It is possible for the polarity between metals to be reversed in certain conditions, e.g. zinc is not protective to steel in certain solutions above 170° F, and although aluminium is normally more electro-negative than zinc, this latter metal has been used sacrificially to protect aluminium.

(5.2) Power-Impressed Cathodic Protection

Power-impressed currents may be used to effect cathodic protection by attaching the negative terminal of a d.c. source to the structure and connecting the positive terminal to a 'ground-bed' of anodes immersed in the electrolyte. The d.c. source causes the transfer of electrons from the anodes to the protected structure, which is thereby rendered cathodic. The reaction occurring at the ground-bed depends upon the nature of the material used. When it is iron or steel the removal of electrons makes the passage of positive ions into the electrolyte easy and the ground-bed corrodes. If it is fabricated from graphite the reaction occurring most readily is the evolution of gas at the anode-electrolyte interface, and consequently anodes of graphite have a very long life. In order to cause protective current to flow it is necessary to use an additional e.m.f. of 2 volts to overcome the contact potential difference which exists between graphite and steel.

The direct voltage required varies from less than 6 volts for applications in sea water to more than 50 volts for structures and anodes in high-resistance soil. Where a.c. power is readily available the most economic method of obtaining d.c. power is to use metal rectifiers; when an a.c. source is not available petrol or Diesel-driven d.c. generators are usually employed, although wind-driven generators have been used to a limited extent. The currents required vary from one or two amperes in the case of a well-coated pipe line to 1 000 amp or more for protecting the steel piles of a large jetty.

The voltage required depends upon the current and the overall resistance of the external circuit. This resistance comprises principally cable resistance, resistance to earth of the structure and resistance to remote earth of the anode ground-bed. Of these, the latter is normally the controlling resistance. Since the power cost is almost directly proportional to this resistance, considerable effort is often expended in reducing it to the lowest practicable value.

(5.3) Anodes and Anode Ground-Beds

Anode ground-beds in soil are normally of two types. If the anode material is steel it is usual to employ scrap rails or piping and to lay them in a trench 2–4 ft deep and to surround them with well-tamped coke (see Fig. 5).

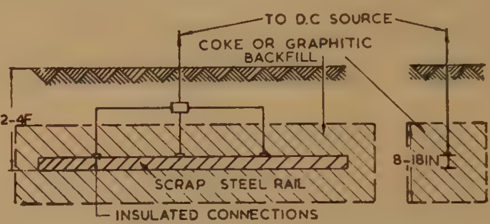


Fig. 5.—Anode ground-bed of scrap steel rail.

The resistance of such a ground-bed is given by the Dwight[2] formula as follows:

$$R \doteq \frac{1\cdot 64\rho_1}{\pi L}\log_\varepsilon\frac{d_1}{d} + \frac{1\cdot 64\rho}{\pi L}\left(\log_\varepsilon\frac{48L}{d_1} + \log_\varepsilon\frac{L}{h} - 2 + \frac{2h}{L}\right)$$

where R = Resistance of the pipe to remote earth, ohms.
ρ = Soil resistivity, ohm-m.
ρ_1 = Resistivity of the special back fill, ohm-m.
L = Length of the rod, ft.
h = Depth of the centre of the rod below ground level, ft.
d = Diameter of the rod, in.
d_1 = Diameter of the special back fill, in.

When the ground-bed is of graphite it is usual to employ cylinders of graphite, which are 3–6 ft long and 3–6 in in diameter, and to mount them vertically in the soil at a spacing of between 8 and 20 ft. The hole into which the anode is placed is made two or three times the diameter of the anode, and the annular space is filled with coke or graphite chips, as shown in Fig. 6.

Various empirical equations have been developed for the cal-

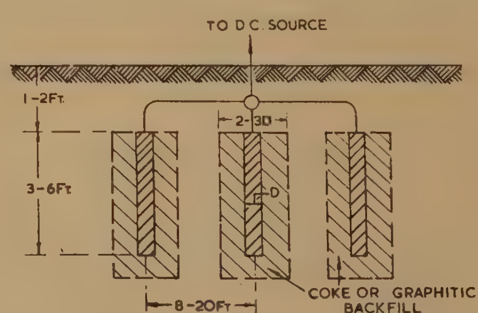


Fig. 6.—Anode ground-bed of vertical graphite rods.

culation of the resistance to remote earth of this type of ground-bed.[2]

The resistance of the ground-bed to earth is proportional to the specific resistance of the electrolyte in which it is buried. The measurement of this quantity is most important and will be referred to later.

The resistance of a ground-bed to earth may vary with time, mainly owing to variation in the moisture content of the soil. Instances have occurred in which a resistance variation of more than 5 : 1 has been experienced. However, this is unusual in cathodic-protection practice, because there is frequently a wide choice in the location of the ground-bed, and sites in areas of low ground level where the permanent water table is close to the surface can be selected.

(5.4) Anodic Cabling

With a power-impressed system all metal on the positive side of the d.c. source is anodic. Thus cables to the anodes and anode connections must be very carefully insulated from the electrolyte; otherwise they will corrode with extreme rapidity. Positive cables are normally polythene-insulated and p.v.c.-sheathed. The foregoing does not apply to sacrificial anodes, as the lead forms part of the protected structure and is therefore cathodic.

(6) MEASUREMENTS

(6.1) Potential Measurements

The measurements of total current, direct voltage, etc., conform to usual electrical practice, but the measurement of potential at a metal-electrolyte interface is not common, and the technique employed in cathodic-protection work requires some explanation.

(6.2) Half-Cells

It has previously been stated that, when a piece of metal is immersed in an electrolyte, a potential is developed at the metal-electrolyte interface, and that this potential depends upon the metal, the solution and the state of the metal surface. When a measurement is to be made of the potential between a metallic structure and the electrolyte in which it is immersed, it is necessary to make an electrical connection to the electrolyte. If this is achieved simply by immersing a steel or copper rod in it, an additional and unknown potential is introduced into the measuring circuit. The connection to the electrolyte is therefore made with a device known as a 'half-cell', which in cathodic-protection practice consists of a pure metal rod dipping into a solution of its own ions. The rod and solution may be contained in a plastic tube with a wooden plug at one end. The capillaries of the wood permit of an electrically conducting path between the solution in the tube and the electrolyte without appreciable contamination of the solution in the half-cell. Sometimes a porous pot of the Leclanché cell type is used as a container for the metal rod and solution. This type of half-cell is frequently not so convenient, especially when making potential measurements in a trench. The e.m.f. between the rod and the solution is fixed if the concentration of the solution is fixed, and hence a constant and known potential is introduced into the measuring circuit. A potential is developed at the junction between the solution and electrolyte, but this is small and is usually ignored. The two most commonly employed half-cells are those comprising (*a*) copper rod dipping into a saturated solution of copper sulphate (see Fig. 7), and (*b*) silver rod coated with silver chloride and dipping into a solution of chloride ions. The former type of electrode is normally used for measurements in soil, and the latter in sea water. Measurements made with a silver/silver-chloride electrode will be approximately 50 mV less negative than those made with a copper/copper-sulphate electrode.

Fig. 7.—Copper/copper-sulphate half-cell.

(6.3) Location of Half-Cell

It has already been stated that corrosion will cease when sufficient current flows through the cathode resistance to polarize this electrode to the open-circuit potential of the anode. Unfortunately, it is not easy to define how much of the electrolyte in front of the cathode comprises the cathode resistance R_c, and considerable controversy has taken place regarding the location of the half-cell when making measurements to determine whether or not a structure is protected. The safest practice is to assume that only a small part of the electrolyte is effective in this respect and to place the half-cell close to the structure. There will be a voltage drop in the electrolyte near a structure, the value of which will depend upon the current density, the electrolyte resistance and geometrical factors. This potential will be added to the metal-interface potential and should be allowed for.

(6.4) Measurement of Specific Resistance of Soil

The electrical resistance of the electrolyte in which the buried structure is located is an important factor, because under aerobic conditions it frequently determines the rate of corrosion of steel and it also determines the most economical size of ground-bed and the output voltage of the d.c. source. The measurement may be made by a single-, two- or four-probe method, but where accuracy is required the latter is preferred. If the current to the outside probes is alternating, or switched direct, with the potential probes switched simultaneously, the effects of electrode polarization and soil currents are eliminated. The four probes are located in a straight line at equal spacings; the outside probes are current sources, and the inside two are for potential measurement. The specific resistance (averaged approximately to a depth a) is given by

$$\rho = 2\pi a R$$

where ρ = Specific resistance of the soil, ohm-cm.
a = Spacing between the electrodes, cm.
R = 'Resistance' of the four-probe electrode system in the semi-infinite conductor formed by the soil, ohms
= Ratio of the potential between the inner probes and the current flowing between the outer probes.

(7) ELECTRICAL SURVEY OF BURIED STRUCTURES

When it has been decided that an installed structure is to be protected cathodically it is desirable to carry out temporary cathodic protection in order to determine the most economical distribution of d.c. power sources and ground-beds, and the minimum a.c. power with which protection can be achieved.

The source of protective current could be either an engine-driven welding generator, or, if a.c. power is available, a transformer-rectifier unit. The negative terminal of the d.c. source is connected to the structure, and the positive terminal to a temporary ground-bed. This latter comprises a number of steel spikes or tubes driven into the soil, or, if the electrolyte is sea water, a piece of scrap steel or iron.

The d.c. source is switched on and the output current adjusted until the minimum structure-electrolyte potential is approximately 0·85 volt against a copper/copper-sulphate half-cell. The generator should be left on for an appreciable time, and the variation of structure-electrolyte potential with time noted. This procedure is necessary for assessment purposes, because the reactions which occur at the metal-electrolyte interface when current flows may take time to reach equilibrium.

When cathodic protection is applied to a structure which has a good coating, so that the potential drop at the interface is largely resistive, the structure reaches its maximum potential within an hour or so. When the coating is poor, and especially when the structure already has a heavy coating of corrosion products, the maximum may not be achieved until the current has been passing for many months. As previously mentioned, an electrolyte containing appreciable amounts of carbonate, calcium and magnesium ion will deposit insoluble salts on a cathodically-protected surface, and slowly build up a resistive layer which reduces the long-term current requirement very considerably.

It will be seen that, although current drainage surveys give useful information with coated structures, the results are not necessarily directly applicable to bare structures, and considerable experience is required to estimate the long-term current and power requirements.

(8) COMMISSIONING

When the cathodic-protection equipment has been installed the transformer-rectifier units are energized and their d.c. outputs adjusted until the minimum metal-electrolyte potential measured anywhere on the system is sufficient for protection. The minimum values acceptable are given in Table 2.

Table 2

Environment	Potential	
	$Cu/CuSO_4$	Ag/AgCl
	volt	volt
Steel in aerobic soil ..	0·85	—
Steel in anaerobic soil ..	0·95	—
Steel in sea water ..	0·85	0·80
Lead in soil	0·55	—

Since the soil-electrolyte potential will not, in general, be uniform, some parts of the structure will have a substantially greater negative potential than is required for protection. When coated lines are being protected the maximum metal-electrolyte potential should not exceed 2·5 volts, since, above this value, the generation of hydrogen at the cathodic surface may cause disruption of the coating.

When the adjustment of the current outputs has been made and the potentials on the system are satisfactory for protection, all the units should be switched off so that the metal-electrolyte potentials return to their 'natural' values. This is necessary in order that interference testing may be carried out.

(9) INTERFERENCE

The currents flowing from a cathodic-protection installation to the protected structure will cause potential gradients to be developed in the soil. If another buried metal structure which is not protected exists in the vicinity, these potential drops will cause current to flow into and from the foreign structure, and, at points where positive current leaves the metal, the corrosion rate will be increased. This effect may be detected by making structure-electrolyte potential measurements with the current source switched off and on at intervals of a few minutes. If, when switching on, the potential increases negatively the foreign structure is being partially protected, but if the numerical negative value decreases the structure is being adversely affected. Generally both types of potential shift will be found in one structure. The simplest way of eliminating an undesirable effect is to make an electrical bond between the protected and foreign structure. This may be made resistive in order to just eliminate the anodic potential change and to reduce to a minimum the current used in partial protection of the foreign structure.

Any value of anodic shift will increase the rate of corrosion, but usually, provided that the shift is not greater than 20 mV, the foreign structure does not require bonding. This anodic shift is only acceptable provided that the foreign structure is not already subject to appreciable corrosion.

(10) JOINT TESTS

It is recommended that, during the initial stages of the preparation of a cathodic-protection scheme which is liable to affect other buried structures, the local electricity, gas, water and Post Office authorities should be contacted with a view to finding the exact disposition of their services in the neighbourhood of the ground-bed and protected structure.

This is best achieved by sending a formal notification that a cathodic-protection scheme is to be installed, together with a drawing of the area and a request that the authority mark on it the location of relevant services or structures.

When the installation is complete, the authorities owning services which are liable to be affected are invited to a 'joint test'. For this the a.c. inputs to the transformer-rectifier are switched on and off at regular intervals (normally 5 min–3 min on and 2 min off), so that the engineers may make measurements to locate the points of anodic shifts (if any) on the services. If such points are found and the shifts are in excess of 20 mV, bonds must be made between the various services so that they are eliminated or made cathodic. Agreement on the type and location of such bonds must be reached.

When all bonds are complete, the installation is switched on and adjusted to give the correct metal-electrolyte potential.

(11) BONDS

Temporary bonds are made by clamping a length of low-resistance wire between the protected structure and the foreign structure. The pipe or other structure should be well cleaned at the part where the connection is made. Any type of clamp can be used, but really good contact must, of course, be made.

The method of making permanent bonds depends very much on the choice of the authorities affected, but generally they themselves will prefer to make the connections.

The joints should be well insulated with several layers of good water-resisting tape.

In considering a complicated network of buried pipes, cables and other structures such as serve a small town or service installation, it would be preferable to protect cathodically all the underground structures at the same time. However, as all the relevant authorities must be of one mind, this rarely happens in practice.

In general, when making bonds from h.v. cable sheaths to gas mains or Post Office cables, it would be preferable to do this using water mains. The attachment to gas mains should preferably be through a heavy block of metal such as steel rail previously tack-welded to the pipe line. This bonding to water mains lowers the resistance to earth of all the bonded structures and thus keeps the voltage to earth as low as possible should any fault develop on the h.v. cables. In certain instances it may be advisable to bring the bonds to a box in which a fuse is installed, but this will involve periodic inspection.

Of course, structures being cathodically protected must be electrically continuous. It is therefore very important to ascertain whether the buried water mains are metal throughout and not partly asbestos, and that mild-steel pipe lines are not insulated at the joints.

(12) INSULATING FLANGES

In some instances it may be desirable to prevent the spread of the cathodic protection to a certain part of the structure. With pipe lines it is common practice to ensure that the jointing material between flanges is an electrical insulator and has sleeved bolts with insulating washers under the heads and nuts.

A typical example is that of a jetty being cathodically protected, but where it is undesirable that current should flow to the shore through pipe lines from the jetty. Insulating flanges would then be inserted in the pipe lines at the root of the jetty.

(13) APPLICATIONS

The following list gives some of the ferrous structures and items of plant to which cathodic protection has been successfully applied:

(*a*) Buried water and oil pipe lines.
(*b*) Buried electrical power and Post Office cables.
(*c*) Marine applications such as sheet and jetty piling in sea and river water.
(*d*) Buried and surface storage tanks.
(*e*) Tubular heat exchangers.
(*f*) Miscellaneous applications to rotary screens, oily-water separators and other items of chemical and power-station plant.

The technique has also been applied to a limited extent to lead and aluminium, but in the latter case, accurate control of the metal-electrolyte potential is essential, because it is possible to cause cathodic corrosion.

Sections 13.1–13.6 outline the factors relating to the most important applications of cathodic protection.

(13.1) Buried Water and Oil Pipe Lines

The literature on the subject of buried water and oil pipe lines is considerable.[3,4,5] Cathodic protection has been applied extensively in both America and the Middle East, and the application in this country is proceeding. The design of the cathodic-protection scheme depends, as previously mentioned, almost entirely on the quality of the coating, if any. When the line is bare the current for, say, an 8 in line will be 30–50 amp/mile, the actual value depending on the nature of the soil, and it would be reasonable to install d.c. sources at intervals of one mile. If the coating is of very good quality a single installation could protect 20–50 miles of pipe line. Wherever possible, it is desirable to locate the installation near a source of a.c. power in order to feed transformer-rectifier units, and this consideration is frequently overriding. On long pipe lines through sparsely populated undeveloped areas where power is not available, Diesel or gas engines are used to supply alternating current for transformer-rectifier units or to generate direct current directly. This equipment is expensive and requires considerable maintenance, but it is still cheap as an insurance in maintaining these very expensive pipe lines in continuous operation.

The protection of buried pipe systems within the refinery or factory plot is determined principally by the question of interference with other buried services such as cable, water, drainage pipes, etc. A large part of the effort required for ensuring satisfactory protection of such systems is devoted to measurements on other structures and carrying out the necessary bonding and insulation. In general, it is desirable to locate the ground-bed as far from the buried services as will provide a satisfactorily uniform distribution of current.

(13.2) Buried Electrical Power and Post Office Cables

The application of cathodic protection to electrical power cables is somewhat limited at present in this country, but it has been used in many instances in the United States. The Post Office has used the method extensively and now has 100 installations using one or more magnesium anodes and more than 80 installations of the power-impressed type.[6]

The principal application is to buried networks of cables, and generally the current requirements are small, i.e. less than 5 amp. Since many of the cables lie in ducts it is not possible to ensure that sufficient current flows to all parts of the metal surface. Hence the best that can be achieved is a substantial reduction in the number of faults occurring—and not the elimination of all corrosion.

When lead is to be protected the potential between the metal and the soil must be more negative than $-0{\cdot}55$ volt measured against a copper/copper-sulphate half-cell.

(13.3) Marine Applications such as Sheet Piling and Jetty Piling in Sea and River Water

Cathodic protection has been applied to practically all types of ferrous structures which are in contact with sea water, e.g. jetties, ships[7] (both external surface and internal ballast tanks), drilling platforms, submarine oil loading lines, etc. In general, such structures are bare or poorly coated, and a current of 5–12 mA/ft^2 is required initially for protection. The alkalinity at the metal/sea-water interface causes a layer of calcium carbonate and magnesium hydroxide to be formed on the protected surface, which results in a reduction in the current requirement. Thus, after the current has been passing for a few months, protection may be achieved by a current density of 3–6 mA/ft^2. The resistivity of sea water is very low—20–30 ohm-cm—and hence the operating voltages for the transformer-rectifier are low, a usual value being 5–25 volts. The current required for protecting a jetty may be very considerable, and values in excess of 500 amp have been used, but at the low voltage used, the actual power required renders the cost of protection economic. In fact, the development of cathodic protection now makes it possible to protect submerged steelwork where previously maintenance was impossible.

(13.4) Buried and Surface Storage Tanks

The principal difficulty in applying cathodic protection to tanks is that all parts of the surface are not accessible, and it is not possible to make potential measurements to ensure that the whole of the surface in contact with the soil is receiving sufficient current for protection. The current density at the centre of the base of a surface storage tank is, in general, less than that at the periphery, and hence it is usual to depress the potential at the periphery to

−0·95 volt in order to ensure that the whole of the base is protected. In order to achieve a reasonably uniform depression of potential around the periphery it is desirable to locate the ground-bed at more than $1\frac{1}{2}$ tank diameters from the nearest point of the base.

The current required for protection depends upon the quality of the coating of the plates of the base. If the base is bare or poorly painted a current of 1–3 mA/ft^2 is required.

(13.5) Tubular Heat Exchangers

The increasing use of sea water and polluted river water for cooling purposes in power stations and oil refineries has accentuated the problem of the corrosion of the end covers and water boxes of tubular heat exchangers. Cathodic protection has been successfully used for the reduction of such corrosion, and Fig. 8 shows the method of installing magnesium anodes on an end cover. In order to control the current flowing from the anodes, these are insulated by plastic bushes and connected through an external resistance to the metal of the cover. Zinc has also been used as a sacrificial metal, but it is only satisfactory in sea water or electrolytes of similarly low resistance, because its driving potential is small.

Power-impressed cathodic protection with platinum or graphite anodes has been used where cooling water exists which has too high a resistivity to allow the use of sacrificial anodes.

(13.6) Miscellaneous Applications

A wide variety of plant, such as rotary screens for cooling water, the ferrous parts of oily-water separators, ferrous sluice gates, etc., have been protected cathodically. When the part to be protected is moving relative to the water and the water is well aerated, e.g. with a rotary screen, current densities of 20–100 mA/ft^2 may be required for protection. Schemes using both sacrificial anodes and power-impressed currents have been operated.

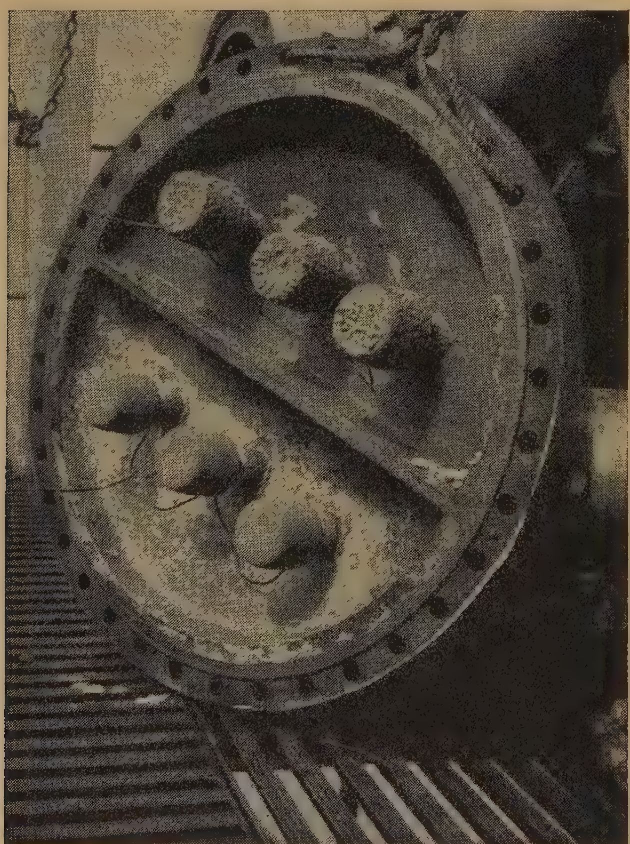


Fig. 8.—Magnesium anodes installed on end cover of tubular heat exchanger.

(14) ECONOMICS

Every structure to be cathodically protected has its own particular problems, and the variables involved are such that each case requires individual design of the system. Therefore, it is not possible to state precisely the cost of applying cathodic protection until a survey and study of the problems involved have been undertaken. However, it is possible, with the experience of a large number of installations, to give the order of the cost of cathodic protection and to illustrate the economic advantages its use offers.

Depending upon the coating quality, length of pipe line and its location, the total cost of an installed cathodic-protection system would usually be 1–5% of the total installed cost of newly coated and buried pipe line. For example, a 10 in-diameter welded-steel pipe, coated, buried and cathodically protected, and laid in a rural area, would cost approximately £10 000 per mile, and the make-up of this cost would be as follows:

	Cost per mile	%
Bare pipe at site	£4 300 =	43
Installing pipe line	£4 400 =	44
Coating the pipe line	£1 000 =	10
Cathodic-protection installations ..	£300 =	3
Total installed cost	£10 000 =	100

The current required for such a system would be only about 1 amp per mile, and so the annual power bill would be less than £5 per mile, which would be negligible as a maintenance or insurance charge on such a relatively high capital investment.

A new coated 10 in-diameter buried pipe line costs about £10 000 per mile with cathodic-protection costs at approximately £300 per mile and negligible running costs. A bare 10 in-diameter buried pipe line would cost about £9 000 per mile with a further £1 400 per mile for cathodic protection, so that the capital costs would be about the same, but the annual cathodic-protection running costs would be about £80 per mile. The best combination both technically and economically is obviously the use of both coating and cathodic protection.

It is advisable to plan to install cathodic protection at the outset, but often it can be used to prevent further corrosion on pipe lines already operating. This is important when £5 million per annum is being spent in this country on replacement of corroded pipes, and the following instance is of interest.

In 1937 a 12 in steel water pipe line just over 6 miles long was laid in Lancashire. Both the inside and outside were coated with bitumen. In 1948 the first leak occurred through corrosion pitting from the outside owing to peaty soils and the activity of sulphate-reducing bacteria. The leak curve (Fig. 9) shows that 25 leaks occurred up to October, 1953, when cathodic protection was applied. In this case the cost of the cathodic-protection installation was £2 800, and the annual running cost is £60.

It will be appreciated that the above information only gives the order of the cost of cathodic protection. Naturally the relative costs would be higher for short lengths of pipe, for smaller diameters, for poorer coated structures and for more complicated networks in congested areas.

The cost of cathodically protecting marine structures such as jetties depends upon the size of the structure, its location, coating and many other factors, but experience indicates that a figure of £20–25 per ampere of required protective current gives a reasonable estimate of the initial outlay when protection is by the

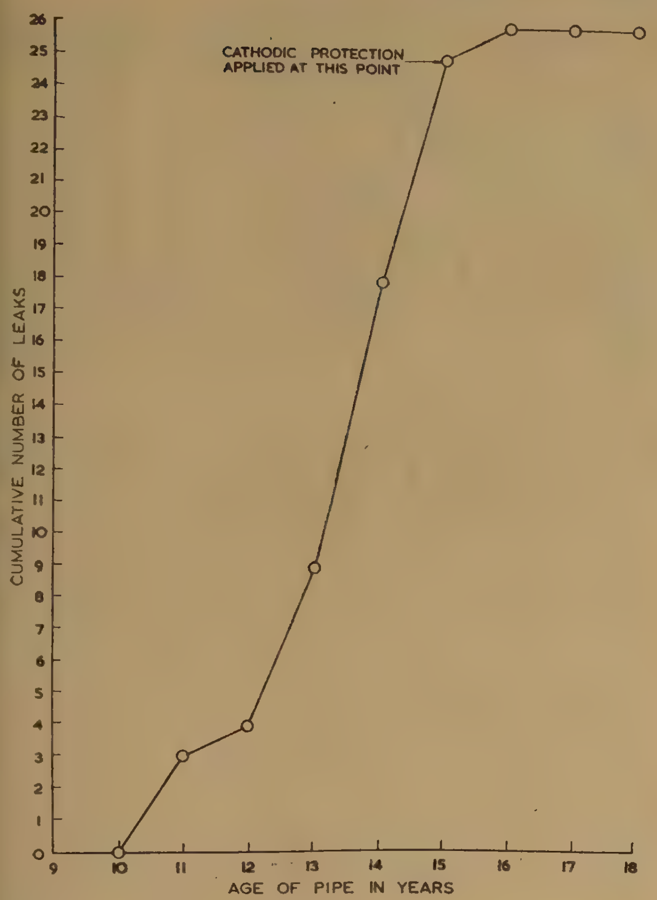


Fig. 9.—Leak record curve of 12 in diameter bitumen-coated water pipe line.

power-impressed method. The figure would be smaller for sacrificial-anode protection, and would probably lie in the range £10–15 per ampere, but the maintenance costs would be considerably higher than for a power-impressed system, since a large part of the initial outlay cost would be reincurred about once every four years.

Magnesium anodes have been installed for the purpose of reducing the corrosion of the compartments of tankers which carry sea water when the ship is in ballast. The cost of such installations depends upon the type of petroleum product which is being carried, i.e. whether it is black oil (crude) or white oil (refined oils). For a medium-size tanker (16 000 tons dead weight) the cost of protecting the centre compartments which are normally used for ballast would be £4 000–6 000, and such protection would last for three to five years, depending upon the method of operating the ship. The cost of re-bulkheading a tanker of this size after 10–12 years in the white-oils trade might well be of the order of £200 000.

(15) CONCLUSION

Cathodic protection has been applied to numerous and diverse structures, and its use has increased very greatly since 1945. It is unlikely that the technique of applying cathodic protection will ever become an exact science because the number of factors involved and the complexity of the geometry of most buried structures make accurate analysis impossible. It is, and will probably remain, a field in which long experience is necessary to achieve the optimum results.

(16) REFERENCES

(1) Morgan. J. H.: 'Fundamentals of Cathodic Protection' (Paper read at a meeting of the Cardiff Graduates and Students Section of The Institution of Electrical Engineers, 10th November, 1955).

(2) Dwight, H. B.: 'Calculation of Resistances to Ground', *Electrical Engineering*, 1936, **55**, p. 1319.

(3) Spencer, K. A.: 'The Water Engineer and Cathodic Protection', *Journal of the Institute of Water Engineers*, 1956, **10**, p. 51.

(4) Uhlig, H. H.: 'The Corrosion Handbook' (Wiley, 1948), p. 923.

(5) Whalley, W. C. R.: 'Cathodic Protection and its Application to the Iraq Pipelines', *Journal of the Institute of Petroleum*, 1949, **35**, p. 705.

(6) Gerrard, J., and Walters, J. R.: 'Cathodic Protection of Telecommunication Cables' (Symposium on the Protection of Cable Sheathing organized by the Corrosion Group of the Society of Chemical Industry on 18th November, 1955).

(7) Carter, L. T., and Crennell, J. T.: 'The Cathodic Protection of Ships against Sea Water Corrosion', *Transactions of the Institution of Naval Architects*, 1955, **97**, p. 413.

DISCUSSION BEFORE THE INSTITUTION, 7TH MARCH, 1957

Mr. W. T. J. Atkins: The idea of reversing the natural flow of electric current in order to oppose corrosion is as old as electrochemistry itself, although there has been a remarkable growth in the application of cathodic protection to large structures abroad, such as pipe-lines and jetties, in the past few years. With certain exceptions, installations in Great Britain have so far been on a relatively small scale, but work has already commenced on the laying of some very extensive pipe-lines for gas distribution which will be provided, right from the start, with this system of protection, and these will be entirely comparable in size with what has been done oversea. Special difficulties may arise through interference by leakage current where cathodic protection is used in areas of dense urban concentration like Great Britain, and to deal with these problems a Joint Committee for the Co-ordination of Cathodic Protection of Buried Structures was formed some two years ago, as announced in the June, 1955, issue of the *Journal*. This is a conference consisting mainly of representatives from public utilities—gas, water, electricity and railway undertakings, with certain others—and was established to keep a register of installations and to attempt to regulate the use of the method in the common interest. Some 450 protective systems are now known, ranging from small Post Office applications on telephone cables to large pipe-lines for transporting liquid and gaseous fuels. One of the most important tasks of the Joint Committee is to standardize methods of testing and surveying for possible interference, and to establish agreed criteria of risk. Eventually it is intended to produce a code of practice which will set a standard of responsible behaviour whereby the conflicting interests of the various parties may be reconciled. This will, it is hoped, prove suitable for adoption by the British Standards Institution, but it may not be ready for a considerable time. One of the difficulties confronting the Committee is that long-established public services inevitably have their own special practices, traditions and legal obligations, which must be respected. Many of these are concerned with bonding and earthing—or with their prohibition—so that where

bonding becomes desirable for the purposes of cathodic protection very complicated problems can occur. For example, the Public Utilities (Street Works) Act has been cited in this connection, and in the absence of decisions in the courts it would not seem safe to assume that it is not applicable, even though cathodic protection was obviously not in the minds of those who drafted the Act. On the ground of technology, progress is being made, and the Committee are assured of authoritative and disinterested scientific advice through the co-operation of the Department of Scientific and Industrial Research and major research associations. At present, interference studies are undoubtedly a heavy burden on members, and serious thought is being given to simplifying and cheapening the procedure for testing, and to finding a fair basis of sharing costs generally. Looking into the future, it may be that, so far as urban and semi-urban conditions are concerned, we are working towards two extreme alternatives, namely either the complete banning of cathodic protection, or universal participation in joint schemes. The paper over-simplifies its subject and is inadequate with regard to the slowly-drifting and seasonal effects which certainly take place. It lays down arbitrary figures for the tolerable positive 'shift' and maximum negative voltages. The Committee are not prepared to recognize any specific limiting conditions until more is known of the outcome of the researches and field trials now in progress.

Dr. F. Wormwell: I have felt strongly for some years that it is most important from the national point of view that full use should be made of this very powerful tool of cathodic protection. Although there is still room for contributions to the fundamental principles, and certainly for more precise data, the broad basis of the subject is well established. The application, however, often bristles with difficulties. These are most evident in the so-called problem of 'interference', to which reference is made in Section 9 of the paper.

I am sorry to see the figure of 20 mV put forward apparently with the implication that it can be used rigidly to decide what is acceptable or not. No one can afford to be dogmatic on this point. The Technical Panel of the Joint Committee have given considerable thought to this matter and have put forward a tentative recommendation that a potential change of this order should be accepted as a limit for the present in order not to delay the installation of important cathodic-protection systems. A decision will depend, however, on many other circumstances, such as the relative importance of the neighbouring structure and the existing corrosion hazard. All these are essentially matters for consultation between the authorities concerned. The Technical Panel and the Joint Committee have therefore supplied the information on their conclusions in confidence to any *bona fide* person or authority, but they have taken the view that it would be unwise to publish the figure in scientific or technical literature. Meanwhile, research is being carried out at Cambridge University by Dr. Hoar and Mr. Farrer to obtain data on which a more definite recommendation can be based.

Dr. W. H. J. Vernon: The paper is primarily—and most appropriately—electrical in nature; yet it may be well to remember that reactions within the electrolyte—whether stimulative or repressive, or whether operating at cathodes or anodes—may greatly influence the corrosion mechanism. If the whole structure is made a cathode, subsidiary reactions may be valuable allies of the electrical protection and may, as the authors have shown, cause a smaller demand upon the available electrical energy.

In Section 2 the authors usefully set out several types of corrosion; but it should not be inferred that the corrosion process itself is fundamentally other than electrochemical in nature. Thus, in 'bacterial corrosion', the sulphate-reducing bacteria stimulate the cathodic mechanism by removing hydrogen from the cathodes; they also stimulate the anodic component, since the secondarily-produced hydrogen sulphide, by precipitating out iron sulphide away from the metal surface, facilitates the entry of more iron ions into the electrolyte.

In the detailed discussion of the economics of cathodic protection in Section 14 the authors have performed a most valuable service; for, in terms of practical politics, it is on economic grounds that cathodic protection, or any other method of corrosion prevention, must be judged. Initial costs must be balanced against costs of maintenance; the latter are well exemplified in the enormous expense of replacing or reconditioning a corroded buried pipe-line. The unique advantage of cathodic protection is that it virtually eliminates the accessibility factor and reduces maintenance to a remote-controlled electrical operation.

I have recently indicated the immense drain upon the national economy brought about by the costs of metallic corrosion generally.* In respect of buried pipe-lines, to which the authors have referred, it became apparent that earlier estimates of the annual cost of maintenance in the United Kingdom had been too low; in the light of available evidence, including costs of reconditioning and replacements, an estimate of at least £20 million annually was believed to be justified. The striking data that the authors have given should be viewed against this background, which serves to show the enormous field of usefulness, in the interests of national economy, that awaits the extended application of cathodic protection.

Mr. L. F. Scantlebury: The Post Office, with several thousand miles of underground cable, is interested in the subject, as it affords a means of protecting cables already in the ground. At present, we have over 700 magnesium anodes and there are 100 power-impressed schemes covering complete exchange areas.

While there is not a great change immediately following the application of cathodic protection, there is a steady drop in the next two to four years to about 40% of the previous fault rate.

Post Office practice follows, in the main, the lines described in Sections 7 to 10 of the paper, although, with regard to the formal notification to other undertakers that a cathodic-protection scheme is to be applied, a 6 in plan is supplied giving details of the plant and telephone exchange, and also information on current output and potential changes. So far as possible we endeavour to keep the minimum potential with power-impressed schemes at $-0{\cdot}6$ volt, rather than the $0{\cdot}55$ volt given in Table 2 of the paper. In practice, of course, a compromise is made between ensuring that we do not appreciably exceed $-2{\cdot}5$ volts near the feeding point and obtaining a minimum of $0{\cdot}6$ volt at the far end of the cable, which may be two or three miles away.

Cathodic effects are referred to in Section 4.2, and our experience with cables in asbestos-cement ducts which can contain free lime is that the application of cathodic protection can give rise to increased faults—at least for the first year or so.

With regard to Section 6.1, we have found that the voltmeter used should have a resistance of 40 000 ohms/volt and should be constructed to the requirements of B.S. 89. For interference tests, where changes in potential may have to be measured to an accuracy of 1 mV, a potentiometer-voltmeter is most useful as the measuring-circuit impedance is practically infinite at the point of balance.

Post Office installations to date are mainly confined to rural districts, where interference with the plant of other undertakers does not cause difficulty. Extension to larger centres must await some agreement on joint schemes being reached between the main undertakers, and it is hoped that the Joint Committee for the Co-ordination of the Cathodic Protection of Buried

* VERNON, W. H. J.: 'Metallic Corrosion and Conservation', *The Conservation of Natural Resources* (Institution of Civil Engineers, 1957).

Structures will be able to reach a satisfactory solution of the many problems involved.

Dr. J. M. Cowan: Early in 1956 the Merseyside and North Wales Electricity Board was informed through the Joint Committee on Cathodic Protection that the Gas Board was going to provide cathodic protection on a gas pipe-line which would ultimately be about 120 miles long. As a first step, it was proposed to apply cathodic protection on a test basis to a 21-mile section between Wrexham and Flint.

There was complete co-operation on the part of everyone concerned with the test. The Gas Board could not have done more; the C.E.A. research staff supplied the test team and test equipment, and the Board co-operated. The section of pipe-line between Wrexham and Flint was 21 miles long, and was of varying cross-section, some 8 in, some 10 in and some 14 in in diameter, none of it being more than four years old. It was all intended to be, and so far as the Gas Board knew was, very well coated, some sections with bituminized asbestos, some with coal-tar enamel and some with Fibreglass, so that effectively the gas pipe-line was well insulated from the earth.

The tests were very lengthy and expensive, but the effort was considered to be justified, since fundamental information was required as a basis for planning of future cathodic-protection installations.

The protection was of the power-impressed type, with two ground-beds in 21 miles. Of 120 places where the Merseyside and North Wales Electricity Board's cables came in the vicinity of the gas pipe, in 20 there was a positive swing of more than 100 mV and in another 60 a positive swing of at least 20 mV, so that on the basis of a 20 mV positive swing being dangerous there were 80 points out of 120 which were affected. The route itself was remarkably good; it passed through pleasant country, and if ever cathodic protection would work, it should work there without unduly interfering with other buried metalwork; yet 80 places have to be dealt with, and it has still not been decided how the problem is to be tacked. Tests are proceeding, and it is hoped that before long a decision will be made by agreement between all concerned on the action to be taken.

In my opinion cathodic protection will have to be allowed in view of the economic advantage to be gained by protecting the pipe-line. At present there has been no suggestion of providing more ground-beds, but one of the first steps should be to put in a few more, because two in 21 miles is not sufficient. Most of the discussion has been about bonding, i.e. who is going to bond and how the bonds should be made. Some want solid bonding, which is probably the most convenient solution, since the bonds can be buried and forgotten; but when one considers what this really involves, it appears that the effect on the cathodic-protection installation will be difficult to forecast, since the extent of the cable sheaths and other buried metalwork with which they are in contact is not known. Cable sheaths and gas pipes of domestic installations get connected to water mains, and the amount of interconnection between cable sheaths, gas mains and water pipes may vary from day to day. The alternative, i.e. to use a resistor in series with each bond, is not practicable; for the Electricity Board it would involve too much testing, and one would have to go back time after time to find out whether it was still effective.

In my opinion it is necessary to have a ground-bed every mile, and, in this event, we might as well run a power cable with the pipe-line.

Mr. W. Lloyd Ellis: When cathodic protection is applied to a buried steel pipe-line, which has a first-class protective coating, the design and installation of the cathodic protection is comparatively straightforward, while the expenditure involved can be less than 1% of the capital cost of the pipe-line. However, owing to the dense networks of underground services in this country, considerably accelerated corrosion is caused in neighbouring buried metalwork. This is the major difficulty to be overcome during the installation of large-scale pipe-line cathodic protection in this country. Theoretically, all points in the vicinity should be individually tested and corrected for potential swings in a positive direction, but this can be excessively costly, and some method of reducing the number of tests must be employed.

This is causing some controversy at present. The only practical method of nullifying interference effects in the neighbourhood of a long pipe-line is by metallic bonding between the pipe-line and the points of potential swing. The making of such bonds can cause some complications. Sometimes there may be an increase in current requirements which is quite excessive, owing to the bond. A further problem is the evaluation of the likelihood of accidents caused by making a metallic bond between a gas main and an electric-cable sheath, taking into account the fact that such bonds often occur inadvertently in any case.

Dr. G. E. Gardam: In the cathodic protection of steel immersed in sea water it is common to use magnesium anodes. These protect satisfactorily, but, when directly connected to the steel, they are wastefully consumed because they usually operate at about $-1\cdot4$ volts and cannot depress the steel beyond about $-1\cdot1$ volts, leaving $0\cdot3$ volt to drive current continuously round the circuit. Insertion of a resistance in circuit limits the high current initially required to polarize the steel and is not satisfactory. The unnecessary current, beside wasting magnesium, may blister paint on the steel.

Consequently, lower-potential anodes are of interest. Zinc is only just base enough to bring steel to $-0\cdot95$ or 1 volt, but it must be virtually iron-free for good service. The ampere-hour capacity per pound is low, thus making it uneconomic. Normal aluminium alloys polarize rapidly and are ineffective. However, a 5% zinc-aluminium alloy has been successfully used for some time in the United States. It gives satisfactory protection and over 500 Ah capacity per pound, owing to its trivalency and low atomic weight.

The organization with which I am associated is at present developing two other aluminium alloys which are still more effective, each of which will produce $\frac{1}{2}$ amp per square foot of anode area continuously whilst holding a potential of $-1\cdot1$ volts; one will, in addition, provide a greater current for the first few days of immersion, by operating at $-1\cdot3$ volts, which is useful to polarize the steel initially. The cost per ampere-hour of these aluminium-alloy anodes is less than that of magnesium anodes, and they are consumed more efficiently. It is hoped shortly to publish the results of laboratory and sea trials.

Mr. J. H. Gosden: Dr. Wormwell mentioned the work being carried out at Cambridge which will provide a basis for fixing a limit of potential change on buried plant as a result of a neighbouring cathodic-protection installation. With regard to power cables, information is also being obtained by making potential measurements where there are galvanic effects due to the use of different metals which are in metallic contact. The occasional faults from this cause have occurred only where the adverse effect is of the order of 100 mV or greater.* Potential changes of the order of 20 mV, acting alone, are unlikely to cause corrosion failures during the normal life of plant. However, the possibility that the adverse effect might be superimposed on some other corrosive influence needs to be taken into account, and frequently there will be little indication of the existing corrosion rate. Even taking this uncertainty into account, I doubt whether it will be found that the figure which has been recommended tentatively by the Joint Committee will differ from the optimum

* Gosden, J. H.: 'The Protection of Power Cables against Corrosion', *Chemistr and Industry*, 13th October, 1956, p. 1069.

value by an amount which is sufficient to cause serious embarrassment either to those who use cathodic protection or to others. However, I agree with previous speakers that further consideration is desirable, particularly in view of the increasing use of cathodic protection.

It would be interesting to have further details of the origins of the various numerical data quoted and of the experience on which they are based. Are the figures for the current density required for cathodic protection the local values at the point where protection has been obtained, or are they average values for particular installations? Can the authors indicate the ratio between these two values? Also what period should elapse between backfilling and testing?

Rather more consideration needs to be given to the type of clamp used for bonding to neighbouring structures than is suggested in Section 11. The criterion should be that adequate contact is maintained. A soldered or welded joint is generally preferable.

Mr. J. H. Morgan: The electrical earths commonly used, i.e. copper or scrap iron in coke breeze, are noble to the common armouring and sheath cable materials. Where cathodic protection is applied to an earthed cable, the majority of the current flows to the earthing system and causes this to polarize to a potential nearly that of the protected cable. If impressed-current protection is used, generally the most convenient location of the cathodic-protection ground-bed is near the substation where the earth plates are also situated. This causes considerable difficulty in achieving any spread of protection, and the large currents flowing in the vicinity of the substation may aggravate interference. We have been working on a series of recommendations for improved practice in this respect which it is hoped to communicate to The Institution at a later date.

Many power stations, and particularly some of the proposed nuclear power stations, rely on sea water or estuary water cooling. Recent developments in cathodic-protection engineering allow the economic use of impressed-current systems to provide complete protection for the inside of the water-carrying pipe-lines and heat exchangers. Long life, of five to ten years, can be achieved economically with no reduction in flow or decrease in efficiency of the heat-exchange equipment. It seems that this field of cathodic-protection engineering will achieve increasing significance in generating stations.

Mr. P. V. Palmer: In Section 5 the authors deal with cathodic protection by means of sacrificial anodes and impressed power. I am disappointed that they have said nothing about the third powerful method, namely the canalization of stray currents from traction systems. Every electrical-engineering student learns that corrosion is caused by stray currents from traction systems which use the running rails as the return conductor. The authors have probably omitted this point because the method has not been developed, particularly in this country, but I should like to have their views on why it has not been developed and whether it has anything to do with the attitude of the organizations responsible for these d.c. traction systems. The use of direct current for traction is decreasing, but the fact remains that there is a great deal of metal being needlessly lost. The authors might perhaps comment on the suggestion that the terms of reference of the Joint Committee for the Co-ordination of Cathodic Protection should be broadened so that it might obtain real and constructive co-operation from the traction authorities in this respect.

Mr. A. C. Vivian: The oil companies have been practising cathodic protection and have records over the past 25 years, so that a great many data are available in regard to the criteria. The figure for negative voltage in Table 2 of 0·85 volt has, over many years, been found to be effective.

The costs which are given in Section 14 are, I am sure, practical costs. I have heard it argued in this country that, in order to protect a buried pipe-line, it can either be coated or cathodically protected. These figures give convincing proof that the really desirable application of cathodic protection is to a coated structure; and, since no one has yet produced a complete covering of a surface, cathodic protection is most economically used to look after the pinholes, or the 'holidays', which exist. The figures give a very good idea of the cost of cathodic protection, and it will be noted that, in the case of bare lines, it is possible to spend £1 400 per mile on it.

It has been stated that Gas Boards are very interested in developing cathodic protection. Most of their lines in the past have been cast-iron mains, and for the successful application of cathodic protection it is necessary to have a bonded line, in the sense that at each joint there must be electrical continuity. With power-impressed current, when the ground-beds can be put a mile or more apart, the bonds have to be heavier, but whether impressed current or magnesium is used, a bond is still necessary.

In this country, where the main problem is interference, the magnesium anode will often be more acceptable than the power-impressed system, because, with the power-impressed system, larger currents have to pass through the earth from the ground-bed to the structure and so are more likely to interfere with other structures.

Mr. J. A. Broughall: The authors have been careful in the paper itself not to mention electrified railways, but in the discussion the impression may have been given that serious interference is caused in their neighbourhood. Preceding speakers have made it clear that British Railways are conscious of their responsibilities to other users and are co-operating in investigations on the extent to which cathodic protection is a useful deterrent. That the railways are not a source of grave corrosion is, I think, clear from the absence of excessive corrosion during the 50 years in which railways have been electrified and from the fact that they would be the first to feel the effects on their own structures. In fact, very few cases of corrosion attributable to electrified railways have come to light, and there has so far been no difficulty in dealing with each individual case on its merits. I agree with the authors' conclusion that it is difficult, if not impossible, to lay down general rules, and each individual case must be considered on its merits.

In terms of an analogy, one may perhaps think of the free ions as fish and of the earth as the sea in which they are swimming. Structures that it is desired to protect can be regarded as the nets in which it is desired to catch or retain the fish. The difficulty is to get all the fish into the right nets. I must have some doubts as to whether the introduction of large systems of cathodic protection is likely to succeed in doing so, having regard to the complicated nature of the earth and the structures involved.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. L. B. Hobgen, K. A. Spencer and **P. W. Heselgrave** (*in reply*): Mr. Atkins states that the paper over-simplifies the subject, and with this we agree, but we feel that this is inevitable in a relatively short general paper. Although the discussion was largely concerned with interference effects, cathodic protection has been applied extensively to such structures as desert pipe-lines, tank bottoms, oil tankers and jetties, where interference effects are non-existent or only of secondary importance. Slowly drifting and seasonal effects are sometimes of importance, as shown in a recently published paper.* With regard to the

* SPENCER, K. A., and NOLAN, H. G. B.: 'Problems involved in the Cathodic Protection of Bare Pipelines', Paper given at Conference sponsored by the Centre Belge D'Étude de la Corrosion, Brussels, 2nd April, 1957.

figures for potential, it was not intended to imply that they were the views of the Joint Committee, but we believe that those given are generally accepted by engineers concerned with the application of cathodic protection.

Dr. Wormwell correctly states that the figure of 20 mV is only put forward as a tentative value which may require modification in the light of future experience. However, since, in the 30 years of intensive application of cathodic protection to ferrous structures, no satisfactory method of relating the metal/electrolyte potential to the corrosion rate has been found, it will doubtless be some considerable time before the effect of small anodic swings can be fully assessed. Cathodic protection is currently being applied to many buried structures in the United Kingdom, and hence it is imperative that a specific figure for allowable anodic shift be given for the general guidance of the authorities concerned.

We are grateful to Dr. Vernon for his contribution and for his reminder that, whatever the name given to a specific case of immersed corrosion, all such corrosion is fundamentally electrochemical.

Dr. Cowan mentions the problem of bonding, and although the particular instance quoted appears formidable, the difficulty of making 80 bonds is not so great as might be expected, given goodwill on the part of all concerned. Simple bonds between the gas main, water mains and Post Office cables can very quickly be made, and might in time become part of the practice of laying lines which are to be cathodically protected. Increasing the ground-beds to a very large number would not normally reduce the problem of interference, since it would then be necessary to select a large number of sites at which electric power and easements were available, and which were sufficiently remote from other buried services not to produce interference effects due to the potential field around the ground-bed itself.

Dr. Gardam's comments on new aluminium anodes are welcomed. The use of aluminium as a sacrificial anode has been restricted greatly by its tendency to anodic polarization, and we look forward with interest to publication of the results mentioned.

In reply to Mr. Gosden, the figures quoted for current density are principally for bare steel and are the local values required for protection. In the case of coated lines the values are averages; the local values at coating imperfections would be very much higher, but depend upon the magnitude of the imperfection present. The time between backfilling and testing has not been found to be of great significance.

DISCUSSION ON

'PROCESSES CONTRIBUTING TO THE BREAKDOWN OF ELECTRONEGATIVE GASES IN UNIFORM AND NON-UNIFORM ELECTRIC FIELDS'*

Dr. A. E. D. Heylen (*communicated*): Recent work[A] on the measurement of the electric strength of hydrocarbon gases has revealed that under uniform-field conditions the sparking potential, V_s, for simple molecular gases is very sensitive to gap illumination. V_s is reduced, not only by ultra-violet illumination, but also by normal laboratory lighting and by daylight, particularly when aluminium electrodes are used. This reduction is attributed to space-charge distortion due to electron avalanches. The space charge is a function both of the number of avalanches per second, I_0, and the size of particular avalanches, $\varepsilon^{\alpha d}$. For instance, when the avalanche size is large, as is the case for hydrocarbon gases ($\varepsilon^{\alpha d} \simeq 10^9$), it will need only a small I_0 ($\simeq 10^4$ electrons/sec) to produce space-charge effects. To keep I_0 low enough to eliminate this effect, tests were carried out in complete darkness with only sufficient illumination of the gap by an ordinary tungsten lamp to produce consistent results.

For non-uniform fields, it is clear that space-charge distortion will be dependent not only on the number and size of the avalanches, but also on the geometry and polarity of the electrode configuration, and will have more influence than in uniform fields. It is interesting to note that Foord[B] has reported pre-breakdown phenomena in compressed gases with a positive point-plane system and little illumination, which are in most respects similar to those found in hydrocarbon gases in a uniform field with excessive illumination.

Thus it is to be expected that, in experiments with non-uniform point plane electrode systems, I_0 will have to be sufficiently reduced, if arbitrary results are to be avoided. Evidence for this is that values of E/p_c reported for the same gases by different workers vary widely. For instance, Foord,[B] using an armoured steel vessel with only three small viewing windows and no particular illumination, reports large values of E/p_c and finds no satisfactory explanation for his somewhat erratic results for $p > p_m$, a range in which other workers have reported a dependence of V_s on illumination. Thus Pollock and Cooper[C] obtain large reductions in E/p_c with irradiation. The values reported in Dr. Howard's paper are about midway between those of Foord and of Pollock and Cooper when using an all-Pyrex glass vessel. He finds appreciable but not large reductions in V_s with increase in illumination.

It seems of importance, therefore, in the type of work reported in the paper, to carry out tests under carefully controlled conditions of illumination. In this connection it may also be useful to record the pre-breakdown conduction currents.

An I.C.I. research fellowship is gratefully acknowledged.

Dr. P. R. Howard (*in reply*): It is stated in the paper that too much pre-ionization may cause reduced spark potential and no irradiation, high values of E/p_c reflecting time-lag effects. The important question is what is the minimum amount of irradiation required; this is an aspect which would be worth studying. Examination of the experimental data also shows that irradiation gives far more consistent corona inception and breakdown values, and the large scatter without irradiation might be misleading.

References

(A) Heylen, A. E. D., and Lewis, T. J.: *British Journal of Applied Physics*, 1956, **7**, p. 411.

(B) Foord, T. R.: *Proceedings I.E.E.*, Paper No. 1568, December, 1953 (**100**, Part II, p. 585).

(C) Pollock, H. C., and Cooper, F. S.: *Physical Review*, 1939, **56**, p. 170.

* Howard, P. R.: Paper No. 2260 M, April, 1957 (see **104 A**, p. 139).

DISCUSSION ON

'POWER SYSTEM PROTECTION, WITH PARTICULAR REFERENCE TO THE APPLICATION OF JUNCTION TRANSISTORS TO DISTANCE RELAYS'*

AND

'A DUAL-COMPARATOR MHO-TYPE DISTANCE RELAY UTILIZING TRANSISTORS'†

BEFORE THE SUPPLY AND MEASUREMENT AND CONTROL SECTIONS, 30TH JANUARY, 1957

Mr. M. Kaufmann: I think that the References show some generosity as well as enthusiasm. Many are of historic interest only, since they are concerned with the outmoded art of thermionic relaying. I have not called it a dying art because it has never really lived, and if it had lived these papers would have been its death warrant.

Fitzgerald (Reference 1 of Paper No. 2085 S) had ideas which were revolutionary in a real sense, and represented a dramatic, even spectacular, break with the traditions of Merz and Price, Beard and Hunter and the other early pioneers. He was lucky, in a way, because his inventions met something of a need. However, 20 years were to pass before his phase-comparison system was used in the United States, and more than 25 years before it was used in this country, although direction-comparison protection, which is a different thing, was used much earlier. Even now, in both phase- and direction-comparison systems, the electro-mechanical relay is conspicuous, not by its absence (which, in my opinion, is devoutly to be wished) but by its presence. The authors, too, have had to introduce one to give the final impulse to the trip coil.

Kennedy (Reference 6) produced an all-electronic direction-comparison system, but he confided that it was regarded as something of a freak and designed primarily to show that it could be done.

Wideröe (Reference 2) was, perhaps, even more ambitious than Fitzgerald, for he devised a range of thyratron relays intended to replace all conventional electromagnetic relays in non-unit systems. Fitzgerald used only a thermionic-comparator relay in a unit system. To my knowledge, there is no application, even now, in which thyratron tubes replace conventional over-current or distance or any other electro-mechanical relay in non-unit systems.

The authors, in choosing to conduct their researches in the domain of non-unit systems, are the spiritual heirs of Wideröe. His thinking, like that of Fitzgerald, outstripped development in the technique of manufacturing electronic components. The question inevitably arises: are the authors in the same position now in relation to the transistor?

Ironically, the transistor has arrived at a time when the gap between the performance of electronic components and the requirements of protection has been virtually closed. We are now at the threshold of another era in which the same high hopes are being raised that the performance of an electronic component will match the ingenuity of eager pioneers engaged in finding opportunities to use it.

If these hopes are to be realized, no relay or protective system based on transistors should be marketed until the reliability of the transistor, in permanence of performance, has been proved under conditions which simulate the worst to be encountered in service. I admit that conservatism has played a small part in retarding progress in the development and application of thermionic relays; the excuse is that protection differs from all other electrical devices in that it is normally quiescent and may be called into activity only once in a long life. Needless to say, its ability to function correctly on that occasion should be beyond doubt. But it is even more necessary that it should remain quiescent at all other times, and ignore all phenomena that do not concern it, including shocks and jars. Furthermore it must do this with a minimum of maintenance.

The electro-mechanical relay is most vulnerable in its resistance to mechanical shock and, to a smaller extent, to sustained vibration. This weakness is widely prevalent and a cause for concern in several countries. I am not implying that relays are worse in that respect now than they used to be. In fact, many are much better. But in times of phenomenally rapid expansion, as the present, the opportunities for involuntarily administering mechanical shocks seem to be unlimited. It is in this realm that the transistor excels, and for that reason alone, its progress in the field of protection will be anxiously watched.

Mr. C. Ryder: With reference to Paper No. 2085 S, the small size of the transistor is an attraction, and it would seem that the orthodox types of relay movement may be meeting a possible competitor in the not-too-distant future. The authors seem to be following an important point of principle in using the transistors as 'on-off' or trigger devices, assuming that I have followed the circuit analysis correctly.

In Paper No. 2177 S the authors were apparently faced with the problem of how to gain stability in the face of transient overreach, and so they evolved the dual-comparator circuit. While this seems to have effected an improvement, it appears to have been achieved largely at the expense of operating time. Are the complications introduced really worth while? Would not the simpler circuit have given the same result if blocked from either measuring or operating for a couple of cycles or so?

Some further thought on the circuit analysis would seem worth while, since the arrangement has yet to grow into a full 3-phase scheme from the simple single-phase diagram shown in Fig. 6, which uses 14 transistors, 25 resistors, 8 rectifiers and 5 capacitors. A phase and earth-fault scheme measuring in three zones would require 18 such assemblies unless some switching arrangement were adopted, which might introduce another complication.

Are the sources of operating and bias voltages intended to be batteries? Is so, something will have to be done about regulation, or the phase-angle difference measured by the transistors T_1 and T_2 will probably vary by a significant amount. Again the time required to charge the capacitor C will vary.

In Fig. 12 one would have expected the family of curves beneath the boundary curve to show some evidence of the kink in the boundary line itself.

Mr. T. H. Walker: In the communication and electronics fields

* ADAMSON, C., and WEDEPOHL, L. M.: Paper No. 2085 S, August, 1956 (see 103 A, p. 379).

† ADAMSON, C., and WEDEPOHL, L. M.: Paper No. 2177 S, September, 1956 (see 103 A, p. 509).

transistors score chiefly because they permit great conservation of power, especially at low levels, and they also make possible considerable space and weight reduction. These features permit the design of transistor equipments with performances not attainable by hard valves or other means.

The papers present a different case, where these advantages, though useful, are not of overriding importance, and the functions described could be done by hard valves. This makes it especially interesting to see transistors considered and to note that, at the conclusion of the work, the view is still favourable, a few early difficulties having been substantially overcome.

The authors state that future work would be directed towards trying to reduce the number of transistors used. No doubt they have something specific in mind, but, in general, it is better to use a few extra components rather than to sacrifice reliability in trying to achieve economy. It seems unreasonable to worry too much about economics at present, as the current prices of transistors are unlikely to be typical.

Transistors are so suitable for electronic switching applications that their use is likely to grow enormously, and this should have a large influence in reducing manufacturing costs. Even devices which at present we regard as purely experimental, such as silicon transistors, having much augmented power and voltage-handling capacity, are, in future, likely to become cheap enough to use. When they are available, the use of transistors in electronic relays, even at relatively high power levels, will become very attractive.

Mr. J. A. Fitzpatrick: When a new protective scheme is developed it must be considered from the aspects of performance, reliability, required maintenance and economics.

From the aspect of performance, I was very pleased to see that the authors gave the relevant data on their schemes in the form of accuracy/range charts. This method does demonstrate the real performance criteria of a distance protective scheme in contradistinction to the old method of giving 'reach' and the fastest operating time. I commend the use of the accuracy/range chart to anyone who has to assess the performance of a distance protective scheme. The authors claim remarkably good performance for their schemes, and give maximum range factors of the order of 60 and 70. Existing distance protective schemes, most of which have proved quite satisfactory in service, usually have maximum range factors of 12 or 14. There are better schemes, but none have the performance of the authors' schemes.

The reliability and the required maintenance of the 'transistorized' relays have not as yet been established, but they have an inherent advantage over their electromagnetic counterparts in their ability to withstand mechanical shock.

The economic aspect cannot be completely established until more experience has been obtained in manufacture and service.

The authors have concerned themselves greatly with transient 'overreach'. This problem has always been with us, and in existing schemes it has often been satisfactorily negotiated by setting the first-stage relay to give approximately 80% 'reach'. One deficiency of the method described by the authors for overcoming transient 'overreach' is the time delay which is incurred so long as the fault current is offset. This may be particularly evident under the conditions of a close-up fault with a consequent high ratio of X/R.

My experience of electronic circuit design is that one can establish a design on paper, but to obtain the best performance the components must be adjusted on the bench. Could the authors express an opinion on the amount of bench adjustment which would be required with their schemes?

One additional field in which the transistors might be considered for application is that of carrier-current protection. Here we already use electronic devices, and any modification which increases the robustness of the equipment and simplifies the power-supply units would be very welcome.

Dr. F. H. Last: Modern protection on high-power transfer circuits is complicated in construction and difficult to commission and maintain. Phase-comparison carrier protection is not successful from the user's point of view; the whole installation is complicated and dependent on many variables. I believe it will be superseded by distance relays.

In protective-gear development we need: ideas, fundamental approach, adequate works and site tests, reliable operation, and simple maintenance.

The authors know the problems and limitations, but in searching for the ideal, they must not sacrifice simplicity or reliability for small gains. Performance is an example. Unnecessary complication may result from the high accuracy over extreme range, whereas a value of Y of 20% is normal and 30% is exceptional. Too much advantage should not be taken of space saving; modern relays tend to be too compact.

It is gratifying to know that development of the pulse relay has been postponed and not discontinued, as stated in Paper No. 2085 S. In Section 7.3.3 of this paper a transient overreach of $1 \cdot 10$ would be acceptable in many cases. In the application of this relay, the use of the memory circuit appears to be essential to clear a close-up 3-phase fault.

With reference to Section 8, I consider the simpler relay with the longer operating time to be superior to the faster relay with slightly reduced accuracy. The authors indicate the lines for future development, and I would give simplicity and greater reliability a higher claim than reduction in cost.

With connections in South Africa it is natural that the authors should seek operational experience in that country. I am quite sure that experience on the British system with the relays connected for indication could be arranged, if the authors so desire.

Mr. A. R. van C. Warrington: The idea of static relays, having no bearings or contacts to maintain, has been considered for a long time, but there have always been drawbacks which have limited the application of the electronic and transductor relays developed so far. Transistor relays appear to be free from these drawbacks and could well be the first acceptable type of static relay. However, even transistor circuits have some problems to be overcome:

(i) The reliable life of the transistor is unknown.

(ii) Transistors are affected by high temperatures and can be damaged by accidental applications of direct current of the wrong polarity.

(iii) A large number of resistors are used in transistor circuits, but the small radio type of resistor is unlikely to be acceptable for protective relays. On the other hand, wound resistors employing wire of reasonable size would be uneconomically large.

(iv) High and variable resistance may occur at connection points at the very low currents and voltages in the comparator circuit ($0 \cdot 5$ to 10 volts at 1 mA or less). This may cause uncertain operation.

(v) A 12-volt supply is not normally available, and separate batteries would be objectionable.

(vi) The tripping relay must be eliminated in order to make the relay really static and hence eliminate maintenance.

(vii) The average power engineer is suspicious of the reliability of electronics and miniaturized circuits.

It is interesting to note that the phase-angle comparator circuits are the transistor equivalent of the induction cup relay, in that the basis of operation is a 90° relation between the quantities compared. What is the advantage of angle comparison over amplitude comparison?

The pulse method has been condemned by the authors, but it has been successfully used in the American electronic distance relays. Is not this worthy of further study because of the positive action without dependence on a time-measuring integrator?

In a 3-phase 3-step distance relay, for phase and earth faults, based on Fig. 6 of Paper No. 2177 S, there would seem to be

a very large number of resistors, rectifiers and soldered connections. Have any steps been taken to make the circuit any more trouble-free than the average radio set, which is considered reliable if it operates with only an occasional failure.

How does the cost of panel space of such a relay compare with that of a distance relay of the electromagnetic type?

Mr. L. B. Johnson: Where the current is increasing rather slowly, one can only switch a relay which has something like four times the power rating of the transistor, but if the transistor is switched quickly from the 'off' to the 'on' state, a very much higher power can be handled.

For instance, with a 24-volt line and a relay taking a current of about 100 mA, i.e. approximately a $2\frac{1}{2}$ watt relay, the voltage drop across the transistor in the 'on' condition is only about 0·4 volt. A current of 100 mA gives only 40 mW, so that, with a comparatively small type of transistor, comparatively large relays can be switched.

Mr. J. K. Webb: I cannot help noting the suspicion which permeates the members of the Supply Section concerning the reliability of electronic equipment. For instance, one speaker appeared to take the radio set as an index. Considering, however, the cut price to which it has to be made and the complexity of the circuit, the surprising thing is that the radio set is as reliable as it is. In other cases, however, where first cost is of less importance, there is no doubt that electronic equipment can attain a very much higher order of reliability. One would not otherwise dare to incorporate such equipment in, for instance, the transatlantic telephone cable. I think it is fair to say that the probability of failure of any given design can now be as accurately forecast in the electronic field as it can in the case of heavy-current equipment.

[The authors' reply to the above discussion will be found on the next page.]

MERSEY AND NORTH WALES CENTRE, AT LIVERPOOL, 18TH FEBRUARY, 1957

Mr. E. Paddison: Static relays have long been considered, and the idea of a completely static relay with no moving parts is very interesting. The most apparent advantages are the lack of bearings and contacts to maintain and the possibility of a completely shockproof construction. Unfortunately, however, there have always been a large number of disadvantages to previous designs of static relays.

Transistor relays seem to have reduced the number, but some still remain. In order to bring these into perspective I would like to ask the following questions.

(i) What is the known reliable life of the transistor?

(ii) What is the effect on transistors of variation in temperature within the range 0–60° C?

(iii) From what source is the 12-volt d.c. supply obtained?

(iv) What kind of resistors are used, and how is the effect of contact resistance at the wire connections minimized when used with these small currents?

(v) The relay shown in the circuit diagrams is not yet completely static since the tripping relay is of the electromagnetic type. Is it proposed to eliminate this? If so, how is it possible to deal with the wide range of circuit-breaker tripping currents of 0·3–30 amp?

(vi) How does the cost and panel space of such a relay compare with that of a distance relay of the electromagnetic type?

Mr. I. A. Reid: The paper represents a step forward in relaying technique, but even if the ultimate development produces a relay with characteristics which improve on those of the electromagnetic types, there will remain a section of line for which fault tripping will be delayed.

The unit schemes which overcome this limitation frequently employ carrier-current signalling, and it seems logical that transistors should be used in this equipment when suitable power ratings become available. Starting requirements could be met with the transistor relay. Some degree of miniaturization would then be possible. This, and its immunity to shock, will make the transistor welcome in the field of system protection.

The need for power supplies is no great disadvantage if we consider the secondary cells now available. Some of these are hermetically sealed and could be within the equipment.

Failure of transistors has not occurred during the authors' experiments. Can they give any information on the types of failure to be expected, and, in particular, does their relay fail to safety?

With an input sensitivity of 1·7 volts, would the accuracy be affected by secondary-wiring induced voltages during fault conditions unless special precautions are taken?

The range of site temperatures to be anticipated is very wide. Can the authors give any indication of the variation of accuracy over the normal service range?

The method of overcoming transient overreach could, perhaps, be simplified by using two relays with their contacts in series, operated from level detectors, one positive and one negative. This would make the introduction of transistors more gradual, which may be advantageous.

The relay, must, of course, be thoroughly tested under site conditions, and I hope that the authors will publish details of their site experience.

Mr. F. M. Pearce: The authors have taken some trouble to achieve a high standard of performance by the employment of a dual-comparator element, and if this is to be maintained in a practical 3-phase 3-zone scheme, it would only be logical to avoid as much switching as possible by providing separate elements for each measuring function. On this basis, a total of 18 elements are required per feeder end, and such an equipment would contain something over 200 transistors, which is indeed somewhat dismaying. This complexity could be considerably reduced by the use of the authors' single-comparator circuit with a short time delay introduced in order to overcome transient-overreach effects. The operating speed of such a scheme would not differ appreciably from that of the dual-comparator circuit because of the time delay inherent in the latter with asymmetrical faults, and it seems to represent a more practical arrangement until the technique of applying transistors to distance measurement has been developed further.

The use of transistor circuits coupled with modern manufacturing techniques should make possible a considerable reduction in the panel-space requirements of distance protective schemes. It is interesting to note that the new schemes do not reduce the number of moving parts in a mho-protective equipment, but merely change the nature of these from sensitive measuring elements into simple on-off switches. The range factors achieved should be high enough to enable transistor relays to be considered for the short lines typical of distribution networks as well as the long high-voltage transmission circuits which are their special field.

The variation in relay characteristic with frequency as depicted in Fig. 13 of Paper No. 2177 S has some significance in view of the reduced margins available for fault arc resistance included within the fault loop, under conditions when the system frequency tends to be slightly below normal.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. C. Adamson and **L. M. Wedepohl** (*in reply*): We agree with Mr. Kaufmann that the development and application of transistorized protective gear relays should proceed with caution. The purpose of the papers served, in the main, to show that it was possible to apply transistors in the field of power-system protection and also to show that one of the major obstacles to the introduction of electronic relays, namely transient overreach, could be overcome.

There are other considerations, however, and Mr. Kaufmann mentions one, namely the susceptibility of mechanical relays to vibration and shock. It should also be mentioned that, by means of electronic circuit techniques, it is possible to devise relays with complex characteristics, which are not obtainable easily by conventional means. Finally, the very low burden on voltage transformers makes possible the application of simple and economical capacitor dividers.

Mr. Ryder discussed the circuit complication and time delay introduced in the dual-comparator circuit. This is a fundamental limitation, and the circuit is of academic value only in that it shows that the problem of overcoming transient overreach is not insuperable. By making use of modified comparator principles and combining static relaying theory with transistor circuits, it has since been possible to devise relays whose time of operation and accuracy are independent of the presence of d.c. components in the fault voltage and current. This has been accompanied by a substantial reduction in the number of transistors and associated components. Two alternative circuits are now available, one using a polarized relay in conjunction with three transistors and the second using a heavy-duty telephone-type relay and six transistors. The minimum operating time of the latter is one cycle, and the majority of faults are detected within three half-cycles of the system. The number of transistors in a complete distance relay terminal is substantially reduced by such means.

With regard to his question about the source of bias potential, batteries were used in the laboratory tests. There is, however, no reason why the supply should not be derived from the station battery through a voltage limiter, e.g. a silicon diode. The relative advantages and disadvantages of sealed cells, accumulators and voltage limiters for this purpose are, at present, under consideration.

Finally, in reply to his question about the kink in the family of curves in Fig. 12 of Paper No. 2177 S, this is not in very great evidence for the following reason. It takes place in the region of the accuracy/range chart where the memory circuit would normally be required to clear faults. Since this region is also that of transient time delay a race takes place between the decay time of the tuned circuit and the transient delay time. If the former is shorter than the latter, there is a failure to operate. Owing to the instantaneous nature of the relay, faults are either detected in fast time or not at all.

We agree with Mr. Walker that the correct operation of circuits is of greater importance than component economy. For this reason the dual-comparator arrangement was developed without regard to economics. However, improved relays have been devised, giving a very great saving in the number of components, with performance superior to that of the dual-comparator type. This point has been discussed in reply to Mr. Ryder's question.

We would like to endorse Mr. Fitzpatrick's remarks about the use of accuracy/range charts. The very clear picture which is obtained of the dynamic performance of a distance relay will probably render other methods of presentation obsolete. He mentions the reliability of transistors. Before they can be applied to power-system protection, data will have to be obtained from the manufacturers in order that an assessment of their useful life can be made. Furthermore, the statistical likelihood of an early failure will have to be estimated. In this context it should be noted that a life-test project was initiated at the Manchester College of Science and Technology about a year ago. Transistors are arranged in groups corresponding to half the normal rating, normal rating and twice the normal power rating. A further group is arranged to have twice the rated collector voltage. A measurement of the important transistor parameters is made each day. No failures have been recorded up to the present, and no significant ageing has been detected.

We agree that the time delay inherent in the dual-comparator circuit is a disadvantage. This point has been discussed in connection with Mr. Ryder's comments, and relays operating to modified circuit principles are free from the defect.

The question of bench adjustment is of fundamental importance if transistor relays are to be applied in practice. In the most recent circuits we have developed, attempts have been made to make the characteristics independent of circuit components contained within the relay circuit. This is simply an extension of the 'on-off' principle used in circuit design. The accuracy of relay settings is therefore determined entirely by the accuracy of components in the replica circuits and the turns ratios of current and voltage transformers. This is a fundamental problem in all protective-gear circuits and will have to be solved by conventional methods: for example, adjustments will have to be provided on reactors in order to ensure that they are within the limits set by the design, since errors in setting will be in direct proportion to the error in reactance.

We agree that transistors might well be applied to carrier protection. The difficulty at present is the availability of a high-frequency power transistor, and this is a problem to which transistor manufacturers are giving a good deal of attention. A transistorized carrier system has been described in the United States, but the power output stage still uses thermionic valves.

We agree with Dr. Last that increased range is accompanied by increased difficulty with regard to transient response and sensitivity. However, it was left that, if the problems could be solved in the most severe case, a more than adequate margin of stability would be available when designing relays to smaller range factors.

With regard to the pulse-type relay mentioned by Dr. Last, it is possible to increase the sensitivity on the polarizing side in order to provide more complete protection for close-in 3-phase faults. However, the problem is one of degree. All polarized distance relays suffer from the disadvantage of not being able to clear close 3-phase faults. This applies to a certain extent even to the memory relay, since it is possible for the fault to be on the system before it is energized, e.g. when the short-circuiting links are inadvertently left on the line.

The question of site testing is most important, and we feel that a very rigorous test programme will have to be conducted before transistor relays are accepted. In particular, the ability of transistors to perform correctly must be studied in countries where the ambient temperature range is greater than in the United Kingdom, e.g. South Africa. An advantage of installing equipment in South Africa is the high lightning incidence, which guarantees that the equipment will receive a reasonable number of faults during the test period. The Transvaal is an excellent area for this purpose, since the number of lightning faults per square mile is higher than in most other parts of the world, and arrangements have been made with the Electricity Supply Commission of South Africa for the installation of a suitable terminal for experimental purposes. We agree, however, that site testing

in this country would be of great value. Not least is the advantage to development engineers of being able to investigate maloperations and failures without undue expense and delay in obtaining equipment for test.

Mr. Warrington raises a number of points in connection with the practical aspects of transistor distance relays. The question of life has already been discussed. With regard to the temperature stability of transistors, we have designed relays which will operate up to ambient temperatures of 125°F without significant change in the relay characteristics. This is mainly a question of circuit design and presents no very great problem. With the advent of silicon transistors it will be solved completely. Application of reverse voltage to transistors will only cause damage if the continuous rating is exceeded for any length of time. This is more of a problem in linear circuits, where the d.c. load resistance in the collector circuit is usually very small, e.g. a transformer or a tuned circuit. In this case, application of reverse voltage will destroy the transistor. However, in our case nearly all the circuits are resistance loaded, which automatically limits the maximum collector power dissipation. Where transformers have been used, the winding resistance has been designed to limit the maximum power to a safe value.

The magnitude of resistors is not a problem confined to transistor relays, e.g. in carrier protection it is necessary to use resistors having values as high as two megohms; since suitable wire-wound resistors are not available, carbon resistors must be used. Experience has shown that, provided that high-stability resistors are used and they are run at a factor of four or more times less than the rating recommended by the manufacturers, little difficulty will be experienced. The early difficulties associated with carrier protection were mainly due to the fact that this criterion was not observed. In the case of transistors the problem is far less severe, since the maximum resistance required is of the order of 50000 ohms and the power dissipation is microscopic.

While no difficulties have been experienced with soldered connections at lower voltages, it is a problem which requires careful investigation. It may be that with relaying systems built up of plug-in units, and working on low voltages, more expensive plating of plugs and sockets, e.g. by the use of gold, should be used.

With regard to his remark about the tripping relay, this could be eliminated by obtaining a tripping pulse for firing a thyratron. In any equipment, this would to a large extent be dictated by the requirements of customers. Most supply engineers are opposed to the use of thyratrons for tripping circuit-breakers and prefer to rely on the use of a separate tripping relay. With regard to the advantage of phase-angle over amplitude comparison, it may be shown that there is a simple relationship between the two approaches; practical convenience may justify the use of one as against the other, e.g. the directional-relay characteristic is most easily obtained by the use of phase-angle comparison.

We condemned the pulse-type relay, mainly because of its inherent instability in the presence of stray system pulses. The problem appears to have been solved in the United States by the use of a tuned pulsing circuit, but the additional complication does not appear to be worth the effort. Whilst the integrating capacitor is not required, a pulsing transformer with associated amplifiers and tuned circuits has to be introduced.

Mr. Warrington mentions, with other contributors, the number of components which are necessary. It is probable that construction of terminal equipment will be on the lines of carrier equipment with a number of accessible sub-assemblies. Figures are not available for the cost of a complete panel, but the indications are that it will be competitive with existing schemes.

We have made use of Mr. Johnson's point for the switching of slave relays. However, the maximum power during switching is usually restricted to about twice the manufacturers' rating of transistors, even when the switching is fast.

We agree with Mr. Webb about the reliability of transistors. While life-test data should be accumulated before applying transistors to power system protection, the indications are that the reliability will be in excess of that of thermionic valves, and since these have been applied successfully to carrier protection, the likelihood of applying transistors is fairly certain.

In reply to Mr. Paddison, until the present, an acceptable definition for a static relay has been one in which comparison of the quantities causing positive operation has been carried out in a static manner; the relays we have described fall into this category. The view is now widely held in the industry that, in addition, the tripping procedure should also be carried out by static means.

We agree with Mr. Reid that the relays described in the papers are not unit systems, and, in consequence, remote end faults will be subject to the usual time delays. He suggests that transistors should be applied in unit systems but does not indicate the type. Phase-comparison carrier protection is applied with difficulty where line lengths exceed 120 miles; for longer lines, protection of the distance-carrier-acceleration type is generally used. In this case, in addition to the carrier equipment, a full complement of distance relays is required. The form of the relays is then the same as for a non-unit distance relay terminal, so that there are the same problems of transient overreach.

We cannot give Mr. Reid a list of all possible failures which might take place. In the relays described, it is possible for an incorrect trip signal to be produced, depending on the type of transistor fault; there is thus a design problem to ensure that the equipment does fail to safety.

It does not appear to have been generally realized in the discussions that test benches of the type described in the paper are capable of more stringent testing of this class of apparatus than any amount of field testing. Furthermore, there are substantial economies to be made in the number of tests which may be carried out, under differing fault conditions, in a given time, e.g. on one occasion about a thousand test shots were carried out in two hours.

In the case of Mr. Reid's last two points, the low input sensitivity should cause no difficulty with induced voltages, provided that long leads do not run parallel to busbars without transposition and large pick-up loops are avoided.

In reply to Mr. Pearce, the total number of transistors may be assessed in terms of 12 relays in a terminal end, each using six transistors per relay. Thus the total number of transistors would be 72, or, in the case of the simpler relay using a polarized element, it would be reduced to 36. However, in the former case it may be possible to make use of grouped relay functions and 72 transistors would therefore be pessimistic.

In connection with the rotation of the mho-circle diameter owing to frequency drift, this is a problem common to all types of 'memory' relay, the analysis of frequency drift in Paper No. 2177 S being perfectly general. The only control available in reducing the drift effect is the Q-factor of the tuned circuit. Since this is very much a function of the speed of operation of the relay, it cannot be reduced indefinitely. It should be noted, however, that two transistor 'memory' relays were tested during fault-throwing tests on site at Ipswich in August, 1956, with tuned-circuit time-constants of the order of 10 millisec. Here the angle of rotation of the mho-circle diameter in the most severe case of frequency drift was less than 10°. This represents a considerable improvement over the conditions indicated in the polar curves of Paper No. 2177 S, and would be acceptable in practice.

DISCUSSION ON 'MINE LOCOMOTIVES'*

Before the North-Western Utilization Group *at* Manchester *9th October*, 1956, *and a Joint Meeting of the* North Midland Centre *and* Sheffield Sub-Centre *at* Barnsley *6th March*, 1957

Mr. P. N. Butler (*at Manchester*): In Section 2.1 it is stated that the maximum weight of a mine locomotive is about 15 tons. I do not consider that it is necessary to have such a restriction, and I understand that locomotives approaching 30 tons weight are shortly to be operated on a trolley-locomotive installation. Incidentally, in America bogie locomotives of up to 50 tons weight are used, thereby reducing the axle load to more reasonable figures and limiting the weight of rail required.

In Section 5 it is stated that no designs have yet been evolved for clasp brakes on mine locomotives, and it is difficult to see the necessity for adopting this arrangement of brake rigging, since that shown in Fig. 4 has superior characteristics to that shown in Fig. 6, where the brake blocks are outside the wheel base. The arrangement of Fig. 4 automatically corrects for the transfer of weight from the trailing to the leading axle during the braking period, whilst the arrangement of Fig. 6 does not. Therefore that shown in Fig. 4 allows a greater braking effort to be developed for the same weight of locomotive, and I regard this as important when considering the braking of trains.

With regard to the traction-motor brushes fitted with Neoprene pads, it would be interesting to know whether there are any results available from the tests which have been carried out. However, it does appear strange that such an investigation has been considered necessary, since the mechanical vibration and shocks sustained by traction motors on main-line locomotives are much greater than on mine locomotives on account of the much higher operating speeds.

In Section 12 the author states that the maximum braking power must be provided on a locomotive, but that it must be kept within limits, whilst he considers a search should be made for more powerful brakes. These are incongruous statements because, if the more powerful brakes can produce braking efforts outside the critical limits, they are essentially ineffective since a skidding condition is initiated, and, as the author points out, the maximum braking effort which a locomotive can produce is that which can be maintained by rail adhesion. It would therefore be interesting to know whether the author has some novel system in mind, and also what is meant by the statement 'more powerful and more efficient brakes'.

Mr. D. L. Hunt (*at Manchester*): In Section 2.3 it is stated that the N.C.B. has laid emphasis on restricting, as far as possible, the number of axles per locomotive to a maximum of two. When larger locomotives are used this results in a higher load per axle, and consequently more substantial rails have to be laid to withstand the loading. How do the costs of laying many miles of heavier rails compare with the use of lighter rails carrying multi-axle locomotives? I realize that the number of driven wheels and the resulting tractive effort must play an important part in the choice of locomotive and rail size.

In Section 5 it is stated that 'no design has yet been evolved which provides for braking on both sides of the wheels; it is invariably by means of brake shoes pressing on one side only'. This type of brake application must produce undesirable loading on the axle bearings. Why cannot diametrically opposed brakes be used? I believe that disc braking has been used on the Continent. Has it been tried in this country? I appreciate that for safety reasons a back-up emergency brake might be required on the track wheels, if the disc brake were on an intermediate shaft. The question of failure to safety is very much in the forefront when any piece of mining equipment is being designed, and I would like to know whether brakes on mine locomotives fail to safety when loss of air pressure occurs. The stopping conditions in an emergency with a lightly or heavily loaded train will differ. In practice, do mine cars tend to be derailed, and if so, has any form of brake governor been tried to prevent it?

I would like to ask the author whether there is greater danger with nickel-iron than with lead-acid cells.

Fig. 1 shows that, in this country, Diesel mine locomotives outnumber battery locomotives. What is the position abroad?

I understand that the Germans are experimenting with an electric locomotive using hydraulic control. They use a battery-driven d.c. shunt motor running at constant speed, and the drive to the wheels is obtained through an oil pump, oil engine, and gear-box.

A battery tender with flameproof plugs and sockets would help battery-changing problems, but I realize that the question of weight and tractive effort of the locomotive plays a major role. However, have there been cases where such a scheme could be used?

Mr. R. Lomas (*at Manchester*): With regard to the trolley-locomotive installation underground at Sandhole Colliery, we have had two or three years' experience under working conditions. The maximum permissible gradient allowed by the Inspectorate for trolley locomotives is 1 in 25, and yet the gradient for battery and Diesel locomotives is 1 in 15. Does the author not consider that it it time the Inspectorate were approached with a view to relaxing the existing Regulations on some of the controversial points, since trolley locomotives show up most favourably on the steeper gradients? Has the author had any reports of trouble on the trolley-locomotive installation owing to earth faults?

Does the author consider that the controls on the double-ended cab Diesel locomotive have been suitably placed; the driver appears to sit sideways in the cab and his vision would appear to be restricted since he is not facing the direction of travel? Has the author any information on modifications which have been made to Diesel locomotives to deal with the nitrous-oxide gases from the exhaust system?

On the question of comparable costs of Diesel, battery and trolley locomotives, different interpretations of the meaning of a ton-mile are encountered which will give considerably varying costs. Taking into consideration the various duties, i.e. running empty, with empty cars, materials and coal, does the author consider that the correct basis is the comparison between the actual number of tons hauled and the actual number of miles run?

Mr. K. M. Pearce (*at Manchester*): The steady increase in the use of locomotive traction underground is encouraging. Some of this growth is concomitant with improvement in locomotive

* Green, T. E.: Paper No. 2106 U, May, 1956 (see 103 A, p. 545).

design, and some is attributable to better understanding of the advantages of locomotive haulage in situations to which they are suited. But how much of the increase is due to the deliberate planning of mining engineers? The coal seams in the United Kingdom are generally unsuitable for horizon mining, and unless mining engineers deliberately plan their development schemes to suit locomotive haulage the admirably designed locomotives now available will not be employed to full advantage. What are the plans for future mines in this respect?

Electromagnetic track brakes on city trams are well known. Messrs. Bavin and Crook, in a paper read before the Manchester Geological Society on 31st May, 1943, described mechanically applied emergency track brakes which have since become popular for man-riding safety carriages using rope haulage, even on gradients steeper than 1 in 3. What is being done to apply this principle to emergency or routine braking of the locomotives themselves? Of course, it would complicate matters if the system were applied throughout each train, but some advantage could surely be gained by, say, hydraulically-applied track brakes on the locomotive itself.

The flywheel locomotive which is now being tried out on a very limited scale is rather fanciful, but it would be interesting to know whether its gyroscopic action would impose any restriction on track layout, e.g. rate of change of gradient of both rails simultaneously, rate of change of super-elevation of the outer rail at the approaches to curves, etc.

The safe disposal of explosive gas from powerful secondary batteries in mines is a very real problem. Adequate dilution with air down to innocuous concentrations is usual. If the problem were referred to research chemists they could advise on the catalytic recombination of hydrogen and oxygen, and if such a reaction could be induced to take place inside each cell continuously and without violence, it could reduce explosion hazards very simply. The reaction is exothermic and extra cooling might be required.

Dr. A. J. King (*at Manchester*): Another factor which might be important when deciding between Diesel and electric operation is the ability of workmen to understand verbal orders and instructions in the vicinity of a locomotive. Diesel engines are notoriously and, in the present state of knowledge, inevitably noisy, while electric motors can be very quiet. When the sounds are increased by the confined spaces with reflecting walls in which mine locomotives work there is a greater danger of mistakes being made with the noisier Diesel engine than with the quieter electric motor.

Mr. R. L. Bassenden (*at Manchester*): All the additional features mentioned, such as rheostatic braking, regenerative braking, track brakes, etc., require room that is not available in a vehicle, the dimensions of which are strictly limited by the radii of curves and other physical limitations. Manufacturers are continually being pressed to include these features, but it is simply not possible without considerably increasing the size of the locomotive, and this is not desirable.

Mr. E. A. Battye (*at Barnsley*): The author points out that the space available between wheels on a 24 in-gauge locomotive is approximately 1 ft 9½ in, which is quite inadequate if the motor rating is to be sufficiently high for the duty demanded of the 13-ton locomotive. In my experience, motors having an output of 75 h.p. can and have been accommodated between the wheels on locomotives operating on this gauge. I agree that a limiting factor for this type of motor is the operating voltage, since this, to a certain extent, 'ties up' the current-handling capacity of the brush gear and may require excessive commutator length. If the operating voltage in the case of trolley locomotives could be increased to about 500 volts, which is standard practice abroad for underground locomotives, I feel that increased output from locomotives could be achieved, and I shall be interested to learn why it has been limited to 200–250 volts in this country.

It is suggested that rheostatic braking provides little or no braking power at speeds less than 4 or 5 m.p.h. This is purely a feature of the design of the locomotives, and in my experience a braking effort as high as 80% of the maximum tractive effort which the locomotive can develop may be obtained by rheostatic braking. Speeds as low as 2 m.p.h. could offer rheostatic braking conditions provided that the resistors and controllers were suitably rated.

Mr. C. L. Forbes (*at Barnsley*): Can the author give any information as to whether regulations have been issued for the use of two battery locomotives in tandem? If so, I would like to have details about the coupling cables.

With regard to braking, the use of roller-bearing tubs has been advocated, but the adoption of this form of axle bearing, with consequent reduction of draw-bar pull, makes the demand for more efficient brakes still more important.

With the present designs of locomotives, the limiting condition is the friction between the wheels and the rail, for the normal type of braking systems. Therefore we should concentrate more on the use of braked tubs or one or more braked cars. Has the author any further information on the adoption of brake cars?

Reference has been made to the gyro locomotive, and as I had the opportunity of a run in the original test model, I would like information as to its adoption or use. The two important points to be considered are, first, the difficulty in arranging for the elaborate control gear to be flameproof, and secondly, the assessment of the gyro effect in the event of a derailment of a locomotive.

Mr. T. E. Green (*in reply*): Experience so far has shown very few instances where a locomotive of more than 15 tons is either necessary or desirable. The case Mr. Butler cites is an exception. The comparison of the brake rigging shown in Figs. 4 and 6 does not necessarily eliminate the possibility of clasp brakes. Any improvement in braking characteristics, however slight, is of value. No results are yet available regarding the trials with traction-motor brushes fitted with Neoprene pads.

With regard to the comments on braking, so long as we have to rely on friction brakes the problem is as stated in Section 12, namely to maintain the braking effort just below the locking point of shoe to wheel and the slipping point of wheel to rail. Whilst there is little factual evidence yet available, there is no doubt that this condition is only infrequently attained. An alternative form of braking, e.g. by the application of a counter-torque force, might well prove a much more powerful braking agency than the application of friction shoes.

Mr. Hunt's question regarding axle loading and rail weight is difficult to answer in simple terms. Locomotives with more than two axles bring many consequent problems of which the unavoidable increase in length is a primary and obvious one. Even so, the N.C.B. have a large number of three-axle Diesel locomotives in service. Disc braking is under close examination at present.

With the present designs, locomotive brakes on Diesel units do not fail to safety when loss of air pressure occurs, but in the case of electric machines the brake application is interlocked with the control circuit. Provision has been made for differential braking power according to the weight of the train in the case of man-riding equipment, but not so far with mineral trains.

Recent investigations* have shown that, under certain conditions, nickel-iron cells generate more hydrogen than lead-acid cells.

Accurate information about locomotives in other countries is

* Hodson, P. H., and Titman, H.: 'The Emission of Gas from Alkaline Cells' (Ministry of Fuel and Power Research Report No. 121, October, 1955).

not easily obtained. There are many Diesel and battery and also trolley locomotives in mines on the Continent, but in the United States the trolley type far outnumbers the others.

The N.C.B. is familiar with the developments in hydraulic control, and if any case can be made out for a practical investigation they will not hesitate to arrange it.

In reply to Mr. Lomas, it is hoped shortly to engage in discussions with the Inspectorate regarding the Trolley Locomotive Regulations. No troubles have been reported at the Sandhole installation as a result of earth faults.

The position of the driver in relation to the controls of Diesel locomotives has been the subject of much consideration, but it is agreed that a great deal more work is needed. The nitrous-oxide gases in the exhaust from the Diesel engine represent a somewhat difficult and obscure problem which has still to be thoroughly investigated.*

The units used for comparing costs must be related to the information needed, and the basis suggested by Mr. Lomas is a useful one for a limited purpose.

* TAIGEL, P. G.: 'Diesel Locomotives in Mines: The Production of Toxic Gases by the Diesel Engine', *Transactions of the Institution of Mining Engineers*, 1951, 111, p. 85.

In reply to Mr. K. Pearce, many schemes for new mines incorporate level or near-level haulage roads. The whole problem of brakes, including the braking of man-riding trains, is under complete investigation, and it is hoped that much detailed information will be made available in the near future.

From practical data now available, there is no indication that the flywheel locomotive will have any of the effects mentioned.

There is some evidence that the difference in the volume of noise from the two types of locomotive is important although not necessarily in the sense that Dr. King implies. We had one very serious accident because of the quietness of the electric locomotive.

In reply to Mr. Battye, the maximum voltage on a trolley-wire system in this country is limited to 250 volts until more experience has been obtained.

In reply to Mr. Forbes, no regulations have been issued relating to the use of battery locomotives in tandem. The use of brake cars is being extended and information is being gathered. The developments on the gyro locomotive have not yet gone far enough to enable any comment to be made on the two points he raises.

DISCUSSION ON 'GERMANIUM AND SILICON POWER RECTIFIERS'*

Before the SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP *at* BIRMINGHAM 8*th October, the* MERSEY AND NORTH WALES CENTRE *at* LIVERPOOL 15*th October, the* WESTERN CENTRE *at* CARDIFF 12*th November, the* SHEFFIELD SUB-CENTRE *at* SHEFFIELD 21*st November*, 1956, *and the* SOUTHERN CENTRE *at* PORTSMOUTH 6*th March*, 1957.

Mr. T. D. G. Wintle (*at Birmingham*): How does the cost of these rectifiers compare with present types in general use, and what is their estimated life?

Mr. W. F. Baker (*at Birmingham*): Will the authors give more information on the performance of germanium rectifiers under high ambient temperatures? For example, if the output of a naturally cooled germanium rectifier is 100% when operating at 20°C, what percentage derating would apply for ambient temperatures of, say, 25 and 30°C?

Mr. T. E. Houghton (*at Liverpool*): The 1 MW rectifier described in the paper went into commercial service at the end of August, 1955, and of the 9800 hours which have elapsed since then it has been on full load at rated capacity, i.e. 4kA at 250 volts, for some 8000 hours, showing an availability exceeding 80%. Initially there were a few minor troubles not related to the germanium cells, and after these had been put right the unit completed a continuous run of 2350 hours, when three cells had to be replaced. A further nine cells failed a few days later, whereupon the manufacturers carried out a thorough investigation into the failures: they found that the trouble was due to the occurrence of peak voltages of about 800 volts on switching off the h.v. supply to the rectifier transformer. About half the cells were affected during these tests, and as a result the makers modified the surge-suppression circuit. Subsequent tests showed that these modifications were effective and the rectifier then completed a continuous full-load run of 4700 hours, when it was shut down for further examination. The cells were in good condition, but it was found that the rectifier losses had increased by about 0·7%. Since these losses were 1·85% of the input when new, this means that the efficiency has decreased by 0·013% in about 5000 hours. If the efficiency continues to fall linearly, it thus appears that it will only be reduced by 1% after something over 30 years of continuous service on full load.

Dr. J. C. Read (*at Liverpool*): Since I was largely responsible for the original decision whereby the rectifier cells described in the paper are normally air-cooled, I should like to learn the case for the directly water-cooled cells that one sees described from time to time in the Press. We learned in connection with mercury-arc rectifiers that water cooling is a source of trouble; but the difficulties of direct water cooling of germanium or silicon cells are much greater, owing to the smaller and more numerous water passages, many of them unavoidably in parallel, and the numerous different potentials, with consequently increased opportunities for corrosion, leakage, choking-up, air-locks, etc. The germanium rectifier operates well at a cell temperature about the same as that desirable for mercury-arc rectifiers; and since the loss to be dissipated is so small, it is an easy matter to provide sufficient area of cooling fins for direct air cooling, even in hot climates. Where the ultimate cooling medium is air, i.e. in the vast majority of cases, direct cooling is far simpler than water-cooled cells and a heat exchanger. Even in the few cases where the ultimate cooling medium is to be water, air-cooled cells still form an attractive arrangement, with a closed air circulating system and an air-to-water heat exchanger (since in any case mains water could not be directly applied to the cells without excessive risk of trouble). I think the only instance where water-cooled cells are attractive is in very-low-voltage sets using single-way transformer connections. In that special case, cells like that on the right-hand side of Fig. 7 can be bolted to a flat water-cooled box instead of to cooling fins—an arrangement that avoids most of the difficulties normally associated with directly water-cooled cells, since the water-cooling system is then all at one (practically earth) potential and can have large passages and no parallel paths, and the replacement of a cel does not involve breaking the water system. For the great ma ority of applications, however, employing double-way or bridg connections, direct water cooling of the cells seems hard to jus ty in the case of germanium, while in the case of silicon I fin it quite incomprehensible.

Mr. T. E. Calverley (*at Liverpool*): Semi-conductor rectifiers

* KINMAN, T. H., CARRICK, G. A., HIBBERD, R. G., and BLUNDELL, A. J.: Paper No. 1936 U, October, 1955 (see 103 A, p. 89).

have a very short heating time-constant, owing to their small mass. It is therefore important that rapid protection should be available to save sound units in the event of a breakdown of any string of units. Fuses seem to provide an excellent solution, but to ensure adequate protection it is necessary to relate the time of operation of the fuse and the maximum possible fault current to the survival time of the units under the fault conditions. Are the fuses commercially available in this country satisfactory, both as regards clearing time and the production of over-voltages?

At first sight, the prospect of using semi-conductor rectifiers on locomotives and multiple-unit trains in conjunction with industrial-frequency electrification appears attractive. However, this subjects them to the worst possible surge conditions which might arise from lightning. A comparison between either a germanium or a silicon rectifier with a mercury-arc device in terms of weight, size and cost would be instructive.

The reference in the Conclusions to power-control devices presumably implies power transistors; do the authors feel that in the very near future we are likely to see the semi-conductor equivalent of the high-power grid-control mercury-arc rectifier?

In many types of apparatus the choice of cooling depends on the application. For low-power equipment, air cooling offers the usual advantages of simplicity, but large quantities of air forced through this type of device in bad atmospheric conditions can become objectionable. Water cooling also has certain advantages in tropical conditions. Moreover, it seems likely that water cooling can lead to a more compact arrangement, especially when applied to basic cell units with mean currents of 200 amp or more.

Dr. W. G. Thompson (*at Liverpool*): The arrival of the germanium rectifier brings home the importance of a good background knowledge, not only in electrical engineering, but also in chemistry, metallurgy and various branches of physics, and to that end I feel it is a good weapon in the hands of those who advocate a broader scientific training for our engineers.

Much can be learned about the behaviour of the germanium rectifier by comparing it with the mercury-arc rectifier. We have solid-gaseous interfaces between the mercury cathode and the mercury vapour and between the vapour and the anode; between these interfaces occur the ionization, current-carrying, deionization recombination and the other effects which enable the mercury-arc rectifier to function. Conditions are exactly analogous in the germanium rectifier, with the positive holes corresponding to ionized atoms, only here the whole phenomenon is taking place in what we have come to regard as a solid material: however, in terms of the ultimate physics there is actually more space than material present per unit volume, and therefore a similar freedom of electron movement.

With regard to protection and the problem of relays and fuses, the real solution lies in making the installation inherently safe by ensuring that the loading does not exceed the working limits of the germanium.

Mr. J. H. Harris (*at Liverpool*): One important field for application of these rectifiers is the electrolytic process, where very heavy currents are necessary. The rectifying units so far produced are quite small, capable of dealing only with relatively small currents. The application of such units to heavy-current processes therefore involves the use of many units in parallel. Furthermore, the output voltage required in these processes is frequently such as to require the connection of numerous units in series. The complete rectifying equipment therefore consists of a very large number of units in series-parallel, which means that the protective devices incorporated to give protection to the various individual groups of circuits are elaborate and expensive. If the rectifying units could be made on a larger scale, a great deal of simplification would be possible. What are the commercial prospects of producing reliable units capable of dealing with hundreds or perhaps thousands of amperes?

Mr. D. B. Corbyn (*at Liverpool*): The junction temperature appears to be the limiting factor during overloads. From the paper and discussion it appears that this is about 60°C (working) in a germanium rectifier, with a possible top limit of 100–120°C during faults. With a silicon rectifier the junction is stated to work at about 150°C, but the failure temperature is not stated. Is this near the melting point of the aluminium counter-electrode (about 660°C) or is there some other limit?

It appears that, if fuses are placed in the arms of a bridge, the arc voltage is imposed on other rectifiers when a fuse blows; but this is theoretically not so if fuses are placed in the three lines feeding a bridge. This has not yet been examined experimentally, but if it is true it seems an attractive proposition to subdivide the rectifier into a number of complete bridges, each with its line fuses. There seems no way out of the difficulty with single-way rectifiers.

For fault indications, when a cell fuse blows it appears best to indicate this fact and to trip a small equipment when the risk of overloading healthy cells is considerable. On a large equipment, with possibly hundreds of cells in parallel, it seems best merely to indicate the existence of a cell fault and to leave the replacement of faulty cells to the next shut-down.

Mr. E. Jacks (*at Liverpool*): Much of the discussion so far has centred on the application of germanium rectifiers to large equipments. What field of application is there for smaller equipment? Will the germanium rectifier supplant the selenium rectifier for such purposes as battery charging in small garages, etc., or if not, at what size and for what sort of application would it become a feasible proposition?

Mr. R. Porter (*at Liverpool*): I should like the authors' comments on the possibility of cooling by bulk immersion of the rectifier elements in oil. Would it be necessary to use an artificial oil, perhaps of silicone base, in view of the high operating temperatures of these rectifiers?

Mr. A. G. Stonebanks (*at Liverpool*): With regard to the possible use of the germanium rectifier in connection with a.c. marine installations, what would be the effect of a greatly varying load? I have in mind a ship with, say, between twelve and twenty 45 h.p. regenerative-type cargo winches installed.

Monsieur R. Poyart (*France: at Liverpool*): Électricité de France and the Central Electricity Authority are jointly studying the prospects of a d.c. link between their respective systems. The authors mention only low-voltage power rectifiers, and give the impression that high-voltage germanium units are not likely to be available in the near future. Is it possible that they could form part of d.c. voltage-generator units for the dielectric tests on the cross-Channel link equipment, for they would permit an output greater than that obtainable with conventional generators?

Mr. K. Rout (*at Cardiff*): The method of evaluating the efficiency of a bridge-connected germanium rectifier is somewhat obscure, and the overall figure of 97% quoted appears to be unjustifiably high. In practice, the operator is generally interested in the mean values of the output voltage and current, and he pays for the r.m.s. input power taken from the supply. For this reason the conversion efficiency is invariably expressed as

$$\frac{\text{Mean output VA}}{\text{R.M.S. input VA}} \times 100\%$$

and this is the definition implied by B.S. 2709.

To illustrate the point, consider a single-phase bridge-connected rectifier. To simplify the calculation, assume a power factor of unity, sinusoidal quantities and an ideal rectifier

(i.e. zero reverse loss and zero forward voltage drop). The expression for the conversion efficiency then reduces to

$$\frac{1}{(\text{Form factor})^2} \times 100\% = \frac{100}{1 \cdot 11^2} = 81\%$$

By similar reasoning, the conversion efficiency of a 3-phase bridge-connected rectifier is given by

$$\frac{1}{3 \times 0 \cdot 74 \times 0 \cdot 82} \times 100\% = 95\%$$

These values are the maximum theoretical efficiencies for the conditions stated. Will the authors define the conditions applicable to the example given in the paper?

The small dimensions of the germanium rectifier also appear to be a limitation, since the thermal mass of the germanium wafer is very small and the junction temperature somewhat critical.

It would appear that the thermal time-constant is very short (less than the operating speed of protective gear), which constitutes a serious disadvantage for many applications and involves additional circuit components to limit the current which can flow under fault conditions or sufficient rectifier capacity to handle the fault current. Will the authors comment on the overload capacity of the device?

Mr. R. A. A. Newman (*at Cardiff*): The authors appear to base the inverse voltage rating of germanium rectifiers on reverse power loss rather than peak inverse voltage. A system basing the rating on the latter appears to have several advantages where high-power rectifiers are concerned, and is one which has been used with considerable success for many years on selenium and copper-oxide rectifiers. This method gives an increased reverse loss in 3-phase circuits, but as a percentage of the total losses the increase is small and could easily be swamped by such safety factors which have to be applied to the cooling arrangement. What are the disadvantages which have led to the rejection of the constant-maximum-peak-inverse-voltage method?

The testing of semi-conductor rectifiers at the production stage involves complicated apparatus, and a simplified but reliable test method is desirable for site checks and customers' acceptance tests. Would a d.c. voltage/current check with carefully selected limits be suitable?

The mobility of holes and electrons with respect to the upper limit of temperature has been mentioned in the paper. Is there a lower temperature limit for satisfactory operation?

Some concern has been expressed about the output-voltage ripple and supply-current harmonics which may be expected from semi-conductor rectifiers. Since these are calculable assuming 'no loss' rectifiers, and the calculations hold reasonably well for mercury-arc and selenium equipments, it would appear that no substantial difference will be observed when using semi-conductors.

Dr. D. Harrison (*at Sheffield*): Why is it necessary to use a single crystal of germanium or silicon rather than a polycrystalline piece?

Breakdown due to excessive reverse voltage or to excessive current is referred to several times in the paper. What happens when this occurs? Is the semi-conductor punctured or does it melt? In Section 10.2.2 it is stated that the high-voltage spikes shown in Figs. 14 and 15 can cause breakdown, even though the voltage is less than the normal breakdown voltage, because they occur just after the cessation of forward current, when the current carriers are still diffused through the crystal. While it is easy to see that there will be a momentary current of relatively high value, this is surely due to the rapid movement of the carriers back to their normal reverse-voltage positions, and will stop when this has been attained.

In the formation of a p–n junction, starting with n-type germanium, the p-section will contain sufficient acceptor elements to neutralize the existing donor element and to provide the positive holes. If it were possible to make the junction without any acceptor in the p-section, would the rectifier be better?

I do not think it is pointed out in the paper that the silicon rectifier has a lower efficiency than the germanium type, owing to the greater voltage drop, as shown in Figs. 8 and 10.

Mr. C. F. R. Bradshaw (*at Sheffield*): The paper describes the existence of reverse currents through the rectifier due to presence of positive holes, which exist for a short time before being combined with electrons. These holes have a certain life before recombination, and this is affected by distance along the crystal and by temperature. Will the authors confirm that, from this, it follows that the unit will not rectify an a.c. supply safely above a certain frequency, indicate the practical limiting frequency and say whether this will vary with the number of phases to be rectified?

The applications of this type of rectifier appear to favour lower-voltage d.c. supplies. Apart from financial comparisons with mercury-arc rectifiers, is there a practical maximum voltage for this type of rectifier?

The paper mentions the use of 3-phase bridges to give 24-, 36-, etc., phase operation for large power outputs. Does this affect the number of phases to be made available by the rectifier transformer, and if so, how does it affect the cost of manufacture and efficiency of the equipment? Also, does it create a maximum acceptable power limit?

Mr. J. B. Machin (*at Sheffield*): A local steel works has about 11 MW of mercury-arc rectifiers and rotary convertors installed to give a 230-volt d.c. supply. These equipments operate at a load factor of about 30% and, on the basis of the curves shown in Fig. 16, the use of germanium rectifiers would save about £6000 per annum.

The steel industry is thinking in terms of casting and forging cranes of up to 500 tons capacity, having about 600 h.p. of motors on the hoist motion. D.C. series motors are the accepted type of drive for such cranes, and it would appear that economies in distribution could be effected by using a.c. supplies with germanium rectifiers installed on the cranes. Do the authors consider that the rectifiers would withstand such arduous conditions of service?

Has any further progress been made with grid control or saturable reactors to give variable and reversible d.c. output?

Mr. D. W. L. Dickinson (*at Portsmouth*): Since both the junction rectifier and the transistor utilize p–n junctions, is it possible that, in the development of efficient high-current rectifiers, consideration has been given to rectifier control by means of external magnetic or electric fields? The field-effect transistor might then lead to an equivalent rectifier design which would help to solve the problems of developing a semi-conductor inverter.

Mr. H. H. Cash (*at Portsmouth*): I was interested to learn that the present supply of flue dust required for the manufacture of germanium rectifiers is obtained from the Midlands Gas Board at about £50 per ton. Since the Central Electricity Authority are also in the flue-dust business, can the authors estimate the likely demand for this primary material?

Messrs. T. H. Kinman, G. A. Carrick, R. G. Hibberd and **A. J. Blundell** (*in reply*): For convenience, our replies will be grouped under the speakers' names.

Mr. Wintle.—Germanium and silicon rectifiers are cheaper than other high-power rectifiers in the lower range of industrial direct voltages, but large-scale production has only just started and greater production will extend the competitive voltage range. The life of these rectifiers has already been proved to be several years and no limit is yet in sight.

Mr. Baker.—The practical limit of junction temperature is 70°C, and may be higher, and the derating required from 20° to 30°C would be about 20%.

Mr. Houghton's account of the operation of the first 1MW rectifier in this country is very interesting. The point we would stress is that, after the initial troubles were overcome, the continuous full-load run of 4700 hours was interrupted only for examination of the rectifier, and this is more typical of the performance than the overall availability over the whole period. The slight increase in losses is due to a change in the type of fuse, and we do not expect further changes to exceed greatly the accuracy of measurement.

Mr. Calverley.—Fuses commercially available in this country are quite satisfactory for use in these rectifiers; the circuits, of course, are to some extent arranged to suit the characteristics of the fuses.

Semi-conductor rectifiers seem ideal for locomotives and motor coaches supplied from a 50c/s overhead wire, and a number of motor coaches of this type are on order. Since the direct voltage of the motors can be fairly high, the mercury-arc rectifier at present shows some advantage in weight, size and cost, but future developments and increased production are likely to reverse this position. Protection from lightning by surge-absorbing circuits is not difficult.

We do not feel that the transistor equivalent to the high-power mercury-arc rectifier will be available in the very near future, but other new devices are under development and show promise in efficient power control. In the meantime, the advantages of semi-conductor rectifiers are sufficient to outweigh the elegance of grid control, except at high direct voltages.

It is true that air cooling in bad atmospheric conditions can be objectionable, but water can also be bad and the best solution is often to use a closed air circuit, as suggested by Dr. Read, cooling the air by standard types of water-tube cooler. The compact arrangement given by water cooling is often an illusion when the need for reserve water supply and the cost of mains water are taken into account.

Mr. Harris.—There seems to be no reason why heavy-current rectifier cells could not be developed, but it is doubtful whether there would be much economic advantage in cells of rating greater than about 500amp.

Mr. Corbyn.—At 250°C the reverse current in silicon rectifiers is considerable, and about 300°C could be regarded as the failure temperature.

If fuses are placed in the lines feeding a bridge, instead of in the arms of the bridge, the over-voltage produced when a fuse blows through cell failure is mainly not imposed on other cells. This position for the fuses, however, does not give satisfactory protection to other cells in the event of a simultaneous failure of two arms in the same bridge; nor does it wholly protect the cells from over-voltage if the fuse blows through a d.c. fault.

Mr. Jacks.—A number of battery chargers and other small rectifiers for 50amp or less have been made with germanium cells.

Mr. Porter.—Cooling the rectifier cells by oil immersion gives useful protection against corrosive atmospheres but is rather expensive and takes more space than forced-air cooling.

Mr. Stonebanks.—Loads which vary considerably have no detrimental effect.

Monsieur Poyart.—For the high voltages envisaged in connection with cross-Channel power transmission some sort of vacuum or vapour-filled valve seems likely to be much smaller and cheaper than germanium rectifiers.

Mr. Rout.—The overall efficiency of 97% given for a germanium rectifier is obtained on a fairly large equipment and is defined as (output power)/(input power) as for most other types of plant. For a 3-phase bridge or any connection giving fairly smooth direct current, output power is practically equal to mean direct voltage multiplied by mean direct current. For the unusual case of a single-phase bridge supplying a resistive load, this product is equal to only 81% of the output power, since about 19% of it appears as ripple. Thus, for this case the 'conversion efficiency' as defined in B.S. 2709 is only 81% even when there is no loss in the rectifier, and the 'true efficiency' as defined above is 100%. B.S. 2709, however, does not apply to rectifier equipments, only to rectifiers, excluding transformers and other apparatus, nor does it apply to germanium or silicon rectifiers.

The overload capacity of a germanium rectifier can be made to comply with the standard industrial rating classes with only a moderate derating of the cells.

Mr. Newman.—The inverse voltage rating of the germanium rectifier is based on a combination of peak reverse voltage and reverse power loss. The use of the latter is a convenient method of applying a realistic working factor of safety, and at the same time is very suitable for production testing. Direct voltage/current measurement can serve as a reasonable method of checking rectifiers, but only if the limits are carefully specified by the manufacturer. Germanium rectifiers will operate quite satisfactorily down to temperatures of −40°C, the only effect being a slight fall in efficiency due to an increase in the forward voltage drop. The d.c. ripple and a.c. harmonics produced by semi-conductor rectifiers, as suggested, are substantially the same as for other rectifiers having no grid control or conduction delay, and can be reduced by smoothing or multi-phase operation.

Mr. Harrison.—Single crystals are used because, in large-area junctions, the current carriers must be free to diffuse over relatively large distances. In a polycrystal the grain boundaries would prevent this and also result in high leakage currents. Breakdown through high reverse voltage usually results initially in the rupture of the barrier at one point, resulting in excessive current, which punctures the semi-conductor wafer. The phenomenon of reduced breakdown voltage during the current-recovery period is still unexplainable. It is always necessary to have acceptor atoms, but not necessarily donor atoms, in the *p*-region.

Mr. Bradshaw is correct in his description of the hole-storage process. This phenomenon will limit the upper frequency for efficient rectification, and will be more serious as the number of phases is increased. Since the high-frequency performance depends chiefly upon the application, it is difficult to give an upper frequency limit for reliable operation. Twelve-phase operation can be obtained with two 3-phase transformers having star and delta primaries. Higher numbers of phases can all be obtained from 3-phase transformers supplied through phase-shift transformers, which do increase the cost and slightly reduce the efficiency. There is no maximum power limit.

Mr. Machin.—If it proved economical, germanium rectifiers could certainly be mounted on the steelworks cranes, as they are on trains, but, of course, the total rectifier capacity would be greater than if one rectifier supplied a number of cranes, since the diversity factor would be small.

Saturable reactors have been used very successfully to give frequent wide variations of rectified current for steel-mill cleaning lines. Reversible d.c. output has not yet been undertaken.

Mr. Dickinson.—It is difficult to envisage a field-effect transistor with a high current and low forward-voltage-drop characteristic. However, a new device may be anticipated when further developed.

Mr. Cash.—The extraction of germanium from the flue dust found in the C.E.A. plant is said to be uneconomical at present.

DISCUSSION ON 'BREAKDOWN UNDER IMPULSE VOLTAGES OF SOLID AND LIQUID DIELECTRICS IN COMBINATION'*

NORTH-WESTERN SUPPLY GROUP, AT MANCHESTER, 16TH OCTOBER, 1956

Mr. A. S. Husbands: The results obtained for mixed oil and pressboard insulation by the authors have a practical application to transformers. However, they used bare metal electrodes, which is not the condition of the winding conductors of a transformer. Results obtained with paper-covered electrodes are shown in Fig. J. The test samples were constructed of

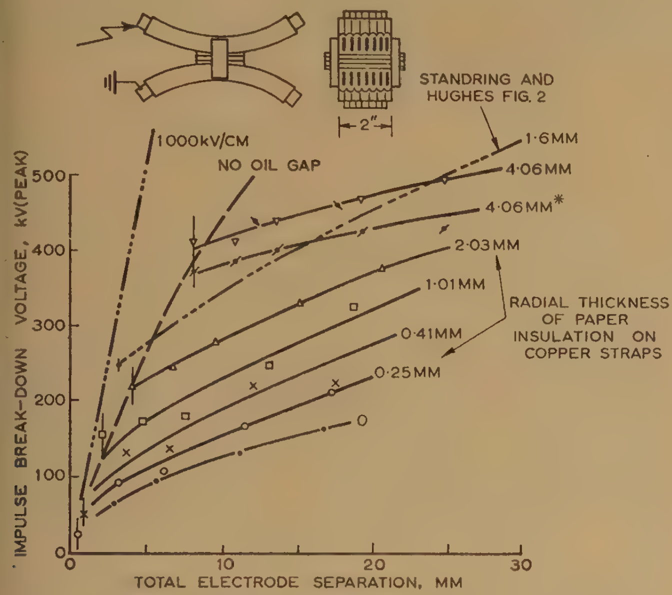


Fig. J.—Impulse breakdown between impregnated paper-covered straps in oil.

1/50 microsec wave.
50–60 kV oil quality.
20° C temperature.
Two–five breakdowns per point.

* Total paper thickness was 2 mm on each strap and 2 mm of crepe paper round each block of straps.

paper-covered copper straps, and they were intended to simulate conditions between discs of a transformer winding. The two blocks of straps were separated by press-board spacer strips, and the samples were well impregnated in transformer oil.

The 1/50 microsec breakdown voltages followed similar trends to the comparable results of the authors, but the levels were generally about 25% below the authors' values. The main difference was in the strength of the paper covering compared with that of a similar thickness of pressboard in the authors' conditions. However, there is no reason to suppose that the paper material was inherently weaker than the pressboard, so that the differences between the results were due to the less uniform field between the paper-covered electrodes. There were no sideways streamers or discharges with the paper-covered samples, but with radial paper thicknesses between 0·4 and 2 mm, there were preliminary streamers in the oil between the two electrodes. The main breakdown, with puncture of the paper covering, usually followed at the same or a slightly higher voltage than that causing streamers. The main breakdown occurred across the edge of the pressboard packing strips.

The authors' suggestion that breakdown was initiated in the oil gap would seem to be true also for the paper-covered samples. Their information on time lags to breakdown was not sufficient for reliable generalizations, but there was a tendency for the lag to decrease with increasing average voltage gradients. The same tendency was obtained with the paper-covered samples, although the individual results varied widely from a mean curve. However, there was a more consistent relationship between time lag and the thickness of paper insulation—irrespective of the oil-gap length. The lag tended to increase initially with increasing paper thickness up to about 2 mm radial thickness. Thereafter it decreases with thicker paper covering. There were irregularities of this curve at about 1–2 mm thickness of paper covering, which was the region of preliminary streamers in the oil between electrodes, and this might be related to some change in the mechanism of breakdown. It is interesting that a similar-shaped curve is obtained when the slopes of the curves of Fig. J are plotted against paper thickness. The quoted results of Messrs. Standring and Hughes also fall into line with these time-lag and slope relationships for paper-covered samples.

Mr. E. G. Wright: The paper adds to our knowledge of insulation flashover, but if one compares the available information on oil and insulation impulse flashover, it is found that the value is very dependent on the electrode and insulation arrangement. The application of basic data, such as those given in Figs. 4, 6, 7 and 8, to design problems is therefore somewhat restricted, owing to the large effect of small changes in electrode shape. For example, a comparison of published information shows that breakdown of oil varies by a factor of about 5 : 1, depending on the electrode arrangement.

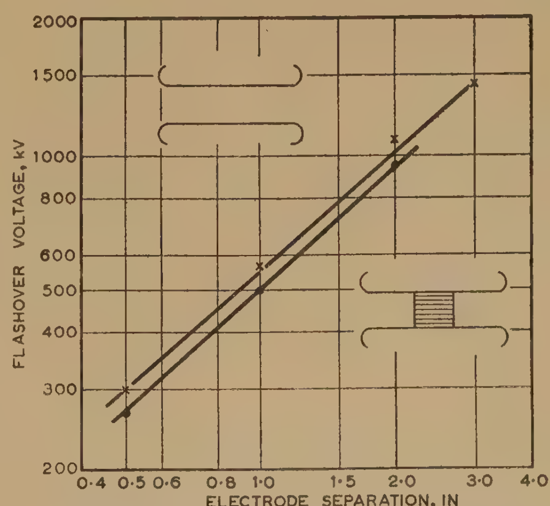


Fig. K.—Flashover voltage of oil and insulation in a uniform field gap.

× Oil only; 1/50 microsec wave.
● Pressboard block; 1/50 microsec wave.

* STANDRING, W. G., and HUGHES, R. C.: Paper No. 2050 S, April, 1956 (see 103 A, p. 583).

Surface breakdown under tangential stress alone varies by a factor of at least 4 : 1. There are few data available for flashover with combined tangential and normal stress apart from Figs. 7 and 8, and as the authors show, this is not greatly dependent on the electrode shape. However, some dependence on insulation thickness, i.e. the degree of normal stress, is to be expected, and perhaps future work at greater thicknesses will confirm this.

Fig. K gives results obtained with an arrangement somewhat different from those used by the authors. The breakdown voltage for oil alone in a uniform field is shown, and also the flashover voltage for dried and vacuum-impregnated pressboard inserted in the uniform-field part of the electrode gap. The electrodes are 12 in in diameter and of the type described by Bruce.* The insertion of insulation reduces the flashover voltage by about 10%, although, in principle, it should not disturb the electric field. It is possible that the reduction is caused by small surface and contact imperfections, although tests show that square blocks have a similar flashover voltage to circular ones.

* Bruce, F. M.: 'Calibration of Uniform-Field Spark-Gaps for High-Voltage Measurement at Power Frequencies', *Journal I.E.E.*, 1947, 94, Part II, p. 138.

Dr. P. R. Howard: It has been suggested that the absence of any effects of a stranded conductor on the impulse strength of cable models is probably due to the use of paper of high impermeability. This has not been shown by tests carried out at the National Physical Laboratory, where there were no observed stranding effects with papers of very low impermeability.

Messrs. W. G. Standring and **R. C. Hughes** (*in reply*): We agree with Mr. Husbands in attributing the lower breakdown voltage of covered conductors for a given total thickness of solid insulation to the less-uniform effective field. We do not expect that our proposed tests with covered conductors will yield a lower puncture voltage for a given system of barrier sheets.

It is interesting to note that, for a separation of 50 mm in a uniform field, Mr. Wright's figure of 1 000 kV for the breakdown of oil agrees with the result obtained with our electrode of 76 mm radius, but that his uniform-field flashover figure for pressboard is about twice what we obtained with large-diameter electrodes pierced by the insulation. The difference is presumably due to the concentration of stress at the inner edge of our electrode.

DISCUSSION ON 'UNDERGROUND LIGHTING IN COAL MINES'*

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 26TH NOVEMBER, 1956

Dr. D. A. Hall: I am particularly interested in fluorescent lighting, because I saw the original installation in the Four Feet Seam at Birch Coppice Colliery, Warwickshire. When this was switched on, the face was found not to be straight; but within a few days the whole place looked tidy, neat and free from all the normal obstructions, etc., which lie about to trip the unwary. As a scientist, not an engineer, I thought then that such lighting would be rapidly adopted, but it was not found possible, on paper, to prove that it was an economic proposition, from the aspects of either increased output or reduced accidents. I feel sure, however, that it must have led to increased efficiency, and I should be pleased if the author would enlarge on the future of this type of lighting.

With regard to so-called 'task standards', I remember a document issued by the National Coal Board suggesting the right amount of light for many types of surface occupation, and there seems no reason why this should not be extended to underground work. When this document was issued I found that my own office was lit to only a fraction of the required standard.

Several years ago, at the request of our production colleagues, we established a central testing station for lamp bulbs, concerned mainly with examining physical dimensions, luminosity and life. At first there were a very large number of rejects, but these have diminished until now the position has become reasonably satisfactory. I should have thought that such test work would naturally have been done by the manufacturers, and I should like the author's comments on the provision of services of this type, which in this case have certainly been profitable to the Coal Board.

Mr. G. W. Milner: The author states that the voltage applied to lead-acid batteries for cap lamps is critical to ± 100 mV. I have seen many lamp rooms having between 10 and 25 charging frames, where the difference in voltage between individual frames greatly exceeds this figure. Does the author feel that hand control of this voltage is adequate?

The author mentions that a face-lighting system can be arranged to provide visual signalling by incorporating a pushbutton switch in the unit, and be so used to stop the machinery in an emergency. This does not meet the requirements of an N.C.B. directive which states that means must be provided for stopping a face conveyor from any point on the face. This is usually done by means of a pull-wire operating a switch in the pilot circuit of the conveyor gate-end box. However, signalling on to the face by the operator before starting a conveyor is most essential in the interests of safety.

In the two face-lighting systems at a colliery with which I have been associated, great difficulty was experienced in finding suitable means of attaching the fitting supporting brackets to the conveyor. In the first, much initial damage was caused to the cable until suitable means of protecting it were devised—no small task when the conveyor was already installed some 2½ miles from the shaft. The second was attached to a conveyor of German origin which had a cable channel incorporated in its structure, and no cables have been damaged in this case. I suggest that conveyor manufacturers incorporate cable channels and suitable bracket attachment points in future armoured conveyors.

Mention has been made of evaluating the benefits derived from face lighting. An attempt was made to do this on the first of the installations with which I have been concerned, considering such points as cleaner coal, increased output and reduction of minor accidents. No trend at all could be established. The men working on the face, however, were very much in favour, since they felt safer for being able to see all round. This is a psychological benefit which cannot be evaluated in financial terms.

Dr. C. J. D. Statham (*in reply*): Following his experience at Birch Coppice Colliery, Dr. Hall's feeling that coal-face lighting should be beneficial, although it has not yet been proved economic, coincides with that of most engineers who have been concerned with such installations. The chief obstacle to a more general application is the difficulty of proving any financial saving to offset the cost of installing and operating the equipment. I feel

* Statham, C. J. D.: Paper No. 2034 U, March, 1956(see 102 A, p. 396).

that the future of mains coal-face lighting lies in combining lighting equipment with some other item of production machinery, such as a loader or armoured conveyor, so that the cost of handling is reduced to a minimum.

It was interesting to learn that the National Coal Board bulb-testing station has proved to be of value. The miners'-lamp manufacturers were prepared to provide such a testing service for bulbs, but the Board preferred to do the work themselves.

In reply to Mr. Milner, hand control of cap-lamp-battery charging voltage is adequate if supervision is well maintained, particularly during the period after a batch of lamps has been put on charge. Systems of automatic control have been developed, but the question of the increased cost involved has to be considered seriously, since the miners'-lamp market is highly competitive.

Although pushbutton signalling by face lighting does not fully meet the National Coal Board's requirements, it would appear to be a good compromise at the moment, and it may be possible to develop an acceptable control arrangement for the lights.

The psychological effect of mains lighting on the face is certainly considerable, and its effect upon the morale of the men may be of value, but I feel that the Board will require something rather more tangible if they are to introduce mains lighting on the coal-face at all generally.

DISCUSSION ON TEMPERATURE RISE IN ELECTRICAL MACHINES*

Before the South-East Scotland Sub-Centre *at* Edinburgh *4th December*, 1956, *the* South Midland Supply and Utilization Group *at* Birmingham *11th February*, *and the* South-West Scotland Sub-Centre *at* Glasgow *10th April*, 1957.

Mr. W. G. Crawford (*at Edinburgh*): The use of thermal networks when calculating the heat flow in electrical machines is a well-established practice. The real novelty in the papers lies in the way they have been applied to the prediction, from test results, of the thermal performance of an existing machine operating on any arbitrarily assigned duty cycle. In spite of using a thermal network, the temperature rise in service is finally estimated from one test curve of potential temperature rise with a second curve giving a cooling correction factor for changes in speed. The method does, therefore, represent a real improvement on the r.m.s. rating, which, as normally applied, does not take into account the effects due to different rates of cooling at different speeds during a cycle. It is now many years since I made it part of my normal design practice to correct the r.m.s. rating for the effects of different rates of cooling.

If a current I_1 flows for a time T_1 and a current I_2 flows for a time T_2, then the r.m.s. value of the current is given by

$$I_r^2 = \frac{I_1^2T_1 + I_2^2T_2}{T_1 + T_2}$$

If the cooling rate during T_1 is n times as great as that during T_2, then the effective value of the current is given by

$$I_e^2 = \frac{I_1^2T_1 + I_2^2T_2}{nT_1 + T_2}$$

The derivation is simple and need not be given here.

When testing large synchronous machines, such as water-turbine-driven alternators which cannot be run on full load while on test, it is normal practice to take an open-circuit and a short-circuit heat run and assume that the resultant temperature rises of the stator winding and core will be the sums of the observed temperatures. The authors' analysis of heat flow obviously provides a method of checking the validity of this procedure.

Electrical machine designers make extensive use of the general properties of affine sets of curves, though it is rarely that they are exploited as thoroughly and systematically as the authors have done. In the design of direct-current machines an accurate knowledge of armature reaction is essential, and design offices now have standard curves showing how it varies with machine loads. When used in the design of a range of direct-current machines, the armature-reaction curves must be related to a reference point on an assumed standard magnetization curve. In the curves I am using, this is the point at which the ratio of ampere-turns on gap and teeth to ampere-turns on gap only is $1 \cdot 2$. Such curves, when properly drawn up, are a typical affine set.

Direct-current machines are widely used in driving paper-making machines. The motors on a modern newsprint machine will vary in size from 70 to 400 h.p. To get the best results, these are designed as a group with very similar operating characteristics. The designs are such that the voltage drop due to armature-circuit resistance is the same in each motor and the total drop in speed from no-load to full load is the same percentage of the no-load speed. The load characteristics of the motors are therefore another typical affine set of curves.

Mr. H. M. Fricke (*at Birmingham*): In the ingenious method of taking up a contact by a phosphor-bronze spring, I should like to know whether the movement of its coils in stray magnetic fields could induce a small e.m.f. in the coils themselves, and whether a small zero error would be introduced?

I should also like to have more details of the various losses which are classed together as 'commutator losses'.

Mr. R. Ledger (*at Birmingham*): Prof. Tustin has described a method of matching a motor to a load based on a series of temperature tests on the machine, but a traction motor designer is often faced with the problem of designing a new motor for a given duty, rather than selecting a standard machine from a range, and in this case it is not possible to refer to test results.

The equivalent-circuit method of calculating machine temperature rise in the design stage is now being successfully applied to the calculation of armature and field temperatures of a wide variety of d.c. traction machines, ranging from small totally enclosed auxiliary motors to highly ventilated traction motors and main generators.

However, because of the nature of its load, the greatest errors arise in the assessment of the duty cycle of a traction motor, rather than in the design of the machine itself, and the motor designer must try to reach a compromise between the worst possible duty, which it would be uneconomic to design the motor to meet without overheating, and that met with in everyday service. Equivalent-circuit methods are of great assistance in

* Bates, J. J., and Tustin, A.: 'Temperature Rises in Electrical Machines as related to the Properties of Thermal Networks', Paper No. 2026 U, April, 1956 (see 103 A, p. 471).
Tustin, A., and Bates, J. J.: 'Temperature Rises in Electrical Machines on Variable Load and with Variable Speed', Paper No. 2031 U, April, 1956 (see 103 A, p. 483).
Tustin, A., Nettell, D. F., and Solt, R.: 'Performance and Heating Curves for Motors on Short-Run Duties', Paper No. 2036 U, April, 1956 (see 103 A, p. 493).

making the numerous temperature calculations involved in this assessment.

Mr. R. Paterson (*at Birmingham*): Prof. Tustin's work in this field is well known. Some engineers are enthusiastic about it, whilst others think that, because there are so many variables, the work is valueless. My view is that the cost of obtaining the knowledge is small compared with the potential savings when the knowledge is applied.

Recently, I was privileged to study recordings of the operations of a 4-ton ingot stripper, on which it might be expected that the cycle of operations would be consistent. On the contrary, it was found that the time, sequence and frequency of operations varied widely from hour to hour, and even more so with a change of operators. A new line of investigation presented itself, namely job analysis, including physical disposition of controls, operator and task; also operator analysis, leading to selection and training of operatives. Thus a study of the paper by Prof. Tustin and Dr. Bates has produced knowledge with secondary, but important, economic advantages.

Mr. W. I. Macfarlane (*at Glasgow*): If every motor in use in the country were correctly rated, the saving in fuel and in distribution capacity could be very large indeed. This is particularly the case with motors for intermittent loading, since, in many cases, running charges may be considerably reduced, particularly if long light-load periods are usual. The saving due to the reduction of light-load losses is very often considerably more than the loss caused by any reduction of efficiency obtained at maximum loads. As a method of assessing what can be taken from a machine under varying conditions the papers therefore deserve close consideration.

Section 1 of Paper No. 2031 casts doubt on the effectiveness of short-time rating of electrical machinery, and in fact the half-hour and one-hour ratings of motors have a limited use. Two machines, one having a large heat-storage capacity and small heat dissipation, i.e. a heavy, large machine with a small fan and the other with small heat storage but good dissipating properties, may have the same short-time ratings; that is to say, after a short-time heat run both will be at the same temperature. During this period, however, the machine with the small heat capacity will have reached nearly its final temperature and will be dissipating the heat due to its losses through the fan, while the other may rise in temperature for some time afterwards, as dissipation is slow and heat is mainly absorbed by storage in the machine parts. If used for similar cyclically varying loads the machine with the large heat storage may be grossly overheated as compared with the other.

If, however, it is possible to assume that the fluctuation of temperature is negligible during the duty cycle, then, as the authors have shown, mean temperatures may be assessed from mean losses and these assumptions are quite justifiable unless the heating cycle approaches the thermal time-constants of the windings. Strictly, the rating should be based on the expected life of the machine, which may normally be taken as the life of the insulation. Insulation, however, deteriorates at an increasing rate with increasing temperature. If we have two machines, one intermittently rated and having a mean temperature rise as calculated by the authors, while the other is continuously rated and has the same temperature rise, it is probably not quite correct to say that the insulation life will be the same in both cases. For normal temperature fluctuations the difference will be negligible, but when the duty cycle is long enough to cause a large variation in temperature during the cycle, this point would require further consideration.

Some time ago I tackled the rating of random loaded generators, such as multi-operator welding machines, on the basis of assessing a duty factor for each operator and then applying statistical methods to obtain mean loads. The ratings were taken as the r.m.s. values of the applied loads, and diversity factors were obtained relating the continuous load to the maximum intermittent load under various conditions of operation. The results followed curves very close to those obtained by practical tests. This could be described as a mean-load method, whereas the authors have used a mean-loss method, which is undoubtedly correct but would appear to lead to considerable difficulty if used as a method for primary design. The authors' method depends on test data giving relationships between non-standard and arbitrarily-fixed standard conditions. Until a considerable body of test experience is built up, this would not tell us how to specify a machine size when only the duty cycle is known, i.e. if the machine is not yet built; yet this is the problem which confronts the user and in many cases the designer. Would the authors comment on the possibilities of their method for primary design?

Prof. H. Tustin, Dr. J. J. Bates and **Messrs. D. F. Nettell** and **R. Solt** (*in reply*): Several contributors to the discussion, including Mr. Ledger and Mr. Macfarlane, raise the question of the applicability of the methods described to predict the temperature rises for a new design; i.e. one for which measured values of the 'potential temperature rises' are not available. Although the relationships given in the paper apply so far as they go, they cannot in themselves resolve this problem. The reason is fundamental. The objective was to relate operational performance to test-bed performance, and to do this directly, without any requirement for the measurement of losses as such or their allocation to the various parts. When a machine is in the design stages the primary question is what its losses will be. Any prediction of temperature rises must, in effect, require prediction of the losses and also of the effective thermal conductances. As Mr. Ledger points out, these can in fact be predicted. If this is done the potential temperature rises and the correction for speed may be estimated, and the suggested procedures applied to estimate the temperature rises on any proposed variable operating schedule.

The familiar method of estimating temperature rises from r.m.s. currents was referred to by several speakers, and Mr. Crawford shows how this method could be adapted to take some account of speed variations. The losses are not, however, proportional to the square of the current, and the temperature rises of the several parts are differently related to the losses. The allowance for extra load losses, part of which are due to eddy currents in the windings, is difficult to make. All such effects are automatically catered for by the method of averaging 'potential temperature rises'.

Mr. Fricke raises the interesting point of the possibility that the spiral wire belt, used as a slip-ring contact, would be subject to stray e.m.f.'s if it ran in a magnetic field.

It appears that movement of a continuous spiral in a stationary magnetic field cannot produce e.m.f. between the ends of the spiral, because the magnetic linkage of the circuit is constant. For any e.m.f. induced in some part of the spiral (where it is linking with a stronger axial field) there must be an equal and opposite e.m.f. in other turns where the axial field is reduced again. This neutralization might not be precise if one of the sections in question were short-circuited by running onto the pulley, but such a combination is unlikely to occur, and in practice no stray e.m.f.'s were observed in the course of our measurements.

DISCUSSION ON 'HIGHLAND WATER POWER—THE DEVELOPMENTS OF THE NORTH OF SCOTLAND HYDRO-ELECTRIC BOARD'*

Before the NORTHERN IRELAND CENTRE *at* BELFAST 13*th November, the* WESTERN SUPPLY GROUP *at* CARDIFF 19*th November, the* SOUTHERN CENTRE *at* BRIGHTON 28*th November*, 1956, *the* SOUTH-WESTERN SUB-CENTRE *at* PLYMOUTH 18*th January, and the* MERSEY AND NORTH WALES CENTRE *at* CHESTER 18*th March*, 1957.

Mr. W. Szwander (*at Belfast*): When considering the possibility and the desirability of utilizing water power for generating electric energy for a supply system, many factors in addition to pure economics must be considered. The relative importance of the various factors affecting the main issue varies, depending both on the local circumstances and on the proportion in which hydro-electric power is likely to cover the total electric power demand of the system. Thus it may be unavoidable to disregard the opposition on sentimental grounds of the local population when hydro-electric power constitutes the only or the main source of power for the community. On the other hand, such drastic action may be inadvisable if only a very small fraction of the demand can be covered by water power, as in Northern Ireland, for example. Owing to the complex nature of the problems, in which other than only technical and economic factors play an important part, a careful and dispassionate study must precede any decisions, and a transfer of the discussions on the subject to the low level of correspondence in the daily Press must be strongly deprecated.

The advent of nuclear power brings a third party into the old controversy between thermal and hydro-electric power. Nuclear power, cheap in time, we hope, will be available away from conventional fuel sources, hence also in the areas now predominantly relying on hydro-electric power. On the other hand, very-high-load-factor operation of nuclear stations, necessary to make them economic, may in some cases stand in the way of hydro-electric developments, if the overall economy of electric power generation in a system as a whole is considered. With less than 3% of energy in our systems being generated by 25% of the installed plant covering the load peaks, it becomes obvious that hydro-electric developments should now above all be carried out with a view to covering the peak loads, i.e. with suitable storage facilities. This is the correct future coexistence between nuclear and hydro-electric generating stations. But, unless very low construction costs per kilowatt can be achieved for the hydro-electric stations, conventional thermal stations may prove more economical.

Mr. J. R. W. Murland (*at Belfast*): As a member of the Electricity Board of Northern Ireland I would like to record our appreciation of the many informal talks between the staffs of the two Boards on technical and administrative matters of common interest.

I was interested to see from the reply to the earlier discussions† that there is a deficiency of £5·5 per annum per consumer in the crofting counties. The Electricity Board for Northern Ireland estimates that it breaks even with a revenue of 21% of the capital cost, which averages approximately £175 per consumer; with our present requirement of 18% per annum guaranteed revenue it follows that our average deficiency is £5·25 per annum per consumer. It is interesting that this is practically the same figure.

The paper mentions the difficulty of screening intakes from descending smolts. I would like to know what the experience has been of electrified screens for this purpose, as I understand some successful experimental work was done with these by the North of Scotland Hydro-Electric Board.

Mr. W. E. Richardson (*at Cardiff*): The plant load factor is very low. It would be interesting to hear what sort of a balance has been struck between steam generation and water power. One wonders if the overall plant load factor might not be improved by either installing less plant in each station or considering pumped-storage schemes.

It would be interesting to know the capital cost per kilowatt installed for each completed scheme. It is realized that this cost must vary considerably, depending upon the amount of civil works, dams, tunnels, etc., and it would be helpful if the cost per kilowatt, where given, could be divided between civil and plant works.

Perhaps we could be told the unit generation cost for steam and hydro-electric stations of the North of Scotland Hydro-Electric Board.

Mr. D. Stephens (*at Cardiff*): I assume that for the altitudes indicated in Section 2.6 transmission lines are designed on ice and wind loadings more severe than those specified in the overhead-line regulations. Details of the practice followed, with some indication of the heights at which it is found to be necessary, would be of interest.

Mr. G. H. Bowden (*at Cardiff*): I think in this country we should recognize the value of the general geological information which is available when constructing dams of the size referred to in the paper. Abroad this information has to be obtained at substantial cost.

I would like to hear whether a repetition of the severe cold spell experienced in this country a few years ago would be likely to cause any substantial reduction in output from the stations referred to in this paper, and whether any substantial expenditure has been incurred in the prevention of possible trouble due to icing.

It is understood that a number of these water-power stations are used for peak load service, which is the reverse of the practice in the case of other systems where water power is used for base load and steam stations are used for handling peaks. If this is so, the speed with which such stations can be loaded would be interesting information, as clearly with long penstocks there is a severe limitation to the rapidity with which fluctuating loads can be dealt with in an upward direction without the use of special surging provisions.

Information relating to the practice of auxiliary system layout is not so generally available as in the case of steam-power stations. With oil servo-controlled governor gear, for example, what time of interruption in auxiliary supply can be tolerated? Is the unit auxiliary transformer supply system generally adopted for auxiliaries, and is full reliance placed on the station transformer for starting up and standby supply, or is it common practice to install auxiliary generating plant?

In those stations where turbines, alternators and exciters are on

* LAWRIE, T.: Paper No. 1909 S, September, 1955 (see 103 A, p. 212). The paper was read at the meetings by Messrs. A. A. Fulton, C. L. C. Allan, L. H. Dickerson, P. L. Aitken, W. R. Brown and P. V. Brown.

† *Proceedings I.E.E.*, 103 A, p. 220.

separate floors, is instrumentation centralized? Is alarm indication similarly dealt with, and what alarms are provided?

From personal knowledge I am sure that the practice of the Authority will be valuable information to those outside this country who have to deal with the construction of similar stations.

The relation between the amount of standby capacity from steam and other prime movers compared with the total capacity of water-power generating plant in the case of the North of Scotland undertaking would be an interesting ratio.

Mr. W. A. Scanes (*at Brighton*): What steps were taken to prevent the corrosion of steel rods, etc., embedded in concrete by the percolation of water through the material, or was a special form of waterproof cement used?

Mr. W. J. Guscott (*at Plymouth*): The Act under which the developments are being carried out clearly and rightly places considerable importance on the subject of amenities, but, as far as I can judge, the Amenity Committee referred to in the paper is concerned only with the building and siting of the hydro-electric stations.

Presumably the majority of the transmission and distribution lines which extend the generated power to the villages and crofts are carried by overhead lines, and reports seem to indicate that these lines are now to be seen throughout the Highlands, notwithstanding the fact that so many parts of the area are classified as beauty spots.

I should like to ask whether the activities of the Amenity Committee do extend to the transmission and distribution lines and, if not, whether the Board experiences the same problems as we experience in the South West of England, where people concerned with the preservation of the moorland and parkland areas are naturally most anxious to keep the number of overhead lines down to an absolute minimum.

Mr. A. G. R. Bell (*at Plymouth*): I would point out that in the West Country there is installed the largest hydro-electric plant in England, also the smallest connected to a public supply, Mary Tavy (3 000 kW) being the largest, and Chagford (21 kW) the smallest. These figures are very small compared with those of the North of Scotland, but they do give a useful contribution to the electricity requirements of the area, the annual output amounting to approximately 10^4 MWh and 10^2 MWh, respectively.

However, I would suggest that with the coming of nuclear power stations the survey of possible hydro-electric installations should now be made on a different basis. In the past the annual run-off available has been the main criterion: now we should look at the storage capacities available, because, in my opinion, it is highly desirable to develop pumped-storage hydro-electric schemes in conjunction with nuclear power stations, bearing in mind the operational difficulties in connection with load variations on nuclear reactors.

I am firmly convinced that in the South West there are eminently suitable sites for the development of pumped-storage hydro-electric stations. There is a high coast-line with rapidly flowing rivers where suitable dams and reservoirs could be constructed without injury to the natural beauties and amenities of the district.

There is at present under construction within a few miles of Plymouth a high-level reservoir for the public water supply, and within three miles of this reservoir there is a suitable site for a secondary reservoir 7–800 ft below, which could give a peak-load pumped-storage capacity of 200 MW.

These possibilities in the interest of the national economy should be fully investigated on the new terms of reference, i.e. pumped storage in place of annual run-off.

Mr. J. Warnock (*at Chester*): With reference to Section 2.5 and Fig. 5, it is a fortunate circumstance that the periods of highest system loading and those of greatest rainfall in the average year in this country very largely coincide. This is a great aid to our water-storage problem in that a 20% water-storage ratio to the average yearly generated load is quite a suitable and satisfactory operating value in this country for a peak-load hydro-electric scheme. In connection with the problem of water storage in the hot climates of the tropics where evaporation is extremely high, a typical solution might be mentioned. On the Tunghabadra Irrigation and Hydro Scheme in Central India, which has a total area of catchment of some 10 000 square miles, the yearly monsoon rainfall of about 43 in, concentrated in the short rainy season, quickly reaches as a flood the storage reservoir with an area of about $1\frac{1}{2}$% only of the total catchment. Complete evaporation in the hot conditions prevailing is arrested by the rapid concentration of the water in a small area with reduced water surface: nevertheless, some 12 in only of the total rainfall is eventually available for irrigation and hydro-electric power.

In Section 6, referring to pumped storage, an allusion is made to the 300 MW North Wales Scheme at Ffestiniog of the Central Electricity Authority, on which construction work has now begun. This project will operate on a difference in elevation between the upper and lower reservoirs of about 1 000 ft and is designed for about 4 hours' peak load operation daily. The plant and general features of the scheme are on a large scale, and as an illustration of the size of the problem which is being dealt with, it can be stated that from the start of pumping (probably about 11 p.m.) until the time at which the upper reservoir is completely refilled (between 6 a.m. and 7 a.m. next morning) a total weight of water of nearly $1\frac{3}{4}$ million tons will have been lifted through 1 000 ft.

Four sets of motor-generators with turbines and pumps each of 75 MW generating capacity will be installed at the power station as vertical-shaft machines. The pump shaft, which will be some 32 ft long, will be connected to the turbine shaft overhead (also about 32 ft long) through an oil-operated clutch. It is of interest to note that the distance between the power station floor and the bottom-thrust-bearing end of the pump will be some 90 ft, with a total overall height of about 110 ft for the whole power unit. The total height of construction of the power station building, with foundations, will be about 160 ft. In operation, while the set is pumping, the turbine spiral casing will be fully exhausted of its water content by compressed air. Generation will be at 16 kV, and the generated voltage will be raised to 275 kV through transformers located behind the power station, with subsequent transmission over double-circuit lines at 275 kV to Connah's Quay, thence to Carrington, near Manchester.

With reference to the civil engineering works, at the upper reservoir two vertical pressure shafts will be sunk below the reservoir floor under the intake gates structure through a vertical depth of about 660 ft. Near the bottom of each shaft two tunnels will take off in a bifurcation and the four pressure tunnels will thereafter run parallel to finish above the power station at portal valve houses; thence the pressure conduits will continue to each generator in the power station by exposed steel pipeline.

The power station and all structures generally will be designed under the supervision of the best architectural knowledge to meet all amenity requirements.

Mr. J. C. Beverley (*at Chester*): It is interesting to note that the anticipated potential of hydro-electric power in the North of Scotland area is now given as $3{\cdot}6 \times 10^6$ MWh by 1966 and that eventually this will treble again. Does this mean that the eventual figure will be about $10{\cdot}8 \times 10^6$ MWh? If so, this compares with earlier estimates which have been made as follows:

1921 Water Power Resources Committee..	$1\cdot88 \times 10^6$ MWh
1938 Committee	$1\cdot972 \times 10^6$ MWh
1942 Cooper Committee	$4\cdot00 \times 10^6$ MWh
1944 N.S.H.E.B. report	$6\cdot274 \times 10^6$ MWh

Could an indication be given as to the main reason for the substantial increase which has occurred over the past few years in the estimated potential?

The proposed installed capacity to give this output has been chosen to give a plant factor of about 30%. Will this figure be used for future schemes or will most of them be of the nature of Loch Sloy, where a low factor is used? It would appear that the speeding up of the atomic-energy programme may have an effect on this, and it would be interesting to know the size of units which are visualized for the future.

Reference has been made in the paper to the wide variety of civil works and machines which have been installed in the existing stations. This variety also extends to the type of control used at various stations, from a fully attended station, as Loch Sloy, with manual starting up of the machines, to fully remote-controlled pumping and generating, as at Sron Mor in the Shira scheme, and fully automatically controlled by time switches and reservoir level, as at Gaur. What form of control is visualized for the large pumped-storage stations which are now being considered?

Mr. C. J. Dickinson (*at Chester*): In Section 2, the paper states that surface pipelines are to be avoided. I would have thought that if surface pipelines were economically justified then that should be the end of it. In most parts of the world surface pipelines are quite common, and when they are put underground it is usually for a reason other than hiding them. The danger in hiding such things is that it leads to other refinements, even to the extent of hiding pipes and valves, etc., inside the station, all of which complicates design and costs more.

It would be interesting to know if the Board has any conclusions to draw regarding relative overall costs between underground and surface stations, since it is possible under favourable conditions for underground stations to be up to 30% less costly than surface stations.*

System stability requirements play an important part in the standardization, with regard to size and speed, of water turbo-alternators, and the inertia constant and overspeed are concerned. Another major, but rather obscure, limitation is the apparent lack of agreement between the various consulting and inspecting bodies, with regard to the factors of safety to be incorporated in a machine. But perhaps the most important consideration is one of economics, i.e. it is most desirable to utilize every kilowatt of available power in any particular scheme, and this almost invariably means tailor-made generators and turbines.

In Section 6.2 some information is given about future schemes. It would be of interest to know the total estimated power potential of the Highlands, including pumped storage, and what proportion of this it is intended to develop?

Mr. D. A. Picken (*at Chester*): The figure given in the paper as the possible output from Loch Sloy of 2000 MW is of considerable interest having regard to the development of atomic energy, which tends to be somewhat less flexible than even the very large sets of coal-fired stations. There will therefore be a greater drive to develop peak-load sources and night loads such as could be made available by pumped-storage techniques.

These developments will, however, bring a considerable number of problems in their train: the difficulty of transmission instability, and also the problem of siting the very large number of overhead conductors in the beauty spots in which pumped-storage systems are likely to be located. It seems that for such purposes the development of d.c. transmission might well be justified, with the possibility of underground cables.

Presumably most of the output from Loch Sloy has a remote load, and much of the energy to drive its pumps would have to be transmitted from at least as far as South Lancashire. A distance of over 200 miles at 2000 MW appears to make d.c. transmission attractive, making economically possible, as it does, the use of underground cables and eliminating the problems of frequency stability.

Mr. C. P. Witter (*at Chester*): I am impressed by photographs of the turbulent water feeding reservoirs. Visualizing the amount of solid in suspension, what is the anticipated life of these reservoirs?

Whereas these hydro-electric developments made a great contribution during the interim period before the full development of nuclear power stations, the Board's chief contribution to the future may be in agriculture, in the provision of rich alluvial plains in the Highlands.

REPLY TO THE ABOVE DISCUSSIONS

Messrs. A. A. Fulton, C. L. C. Allan, L. H. Dickerson, P. L. Aitken, W. R. Brown, P. V. Brown (*in reply*): Mr. Szwander emphasizes the desirability of developing wherever possible suitable hydro-electric schemes to meet peak loads. This is true if it continues to be necessary to operate nuclear stations at high load factor in order to make them economic. The capital cost per installed kilowatt, however, is not the real yardstick of comparison between hydro-electric and thermal plants. It is the cost of production of a kilowatt-hour at the appropriate load factor.

Mr. Murland asks about the Board's experimental work with electric fish-screens. Much of the work done was described in a paper† read before the Royal Society of Edinburgh, but, briefly, the Board's operating experience has been less successful for descending than for ascending fish. An electric screen to divert descending smolts was tried at the Dunalastair intake on the Tummel Scheme and, whilst it achieved some success, it was not sufficiently successful to justify continuation of the experiment. It suffered, not only from the disadvantage that any smolt affected by the electric field continued to drift through the screen, but also because it had to be fitted into existing structures. Almost complete success has, however, been achieved in diverting ascending fish by electric screens. Fish have been prevented from entering the Morar tail-race by an electric screen which has been in operation for several years. Similar arrangements at other tail-races are being planned, and some encouraging experience has also been obtained in the use of electric screens to stop completely the ascent of fish at selected places.

In reply to Mr. Richardson, the average capital cost per installed kilowatt on the post-war schemes completed or under construction is £175, of which about £14 is for electrical and mechanical plant. In 1956 the cost of generation per kilowatt-hour was 0·64d. for the hydro-electric stations (80% from the post-war schemes), and 0·93d. for the steam stations of the Board. Steam power has been about 25% of total production.

Mr. Stephens asks about the practice followed in designing transmission lines to run over high and exposed positions. The lines are strengthened partly by placing standard towers closer together, and thereby reducing the design span lengths to 80%

* Jaeger, C.: 'The New Technique of Underground Hydro-Electric Power Stations', *English Electric Journal*, June, 1955, **14**, No. 2, pp. 3–29.

† Lethlean, N. G.: 'An Investigation into the Design and Performance of Electric Fish-Screens and an Electric Fish-Counter', *Transactions of the Royal Society of Edinburgh*, 1951–3, **62**, Part II, No. 13, pp. 479–526.

of the normal specification figure, and partly by reducing from 8 000 lb to 5 000 lb the allowable maximum line-conductor tension at 22° F under the specified working conditions. In some cases foundations are also made heavier.

With regard to icing trouble, measures so far taken include the provision of special switching arrangements at substation terminals to facilitate the application of heating currents and the installation in one case of an ice-detection device.

In answer to Mr. Bowden, it can be said that, so far, periods of cold weather have not caused any reduction in the Board's hydro-electricity output. Severe frosty conditions normally do not begin in Scotland until January, when storage is usually at its maximum. It would be a very exceptional cold spell which lasted long enough to deplete seriously this substantial storage before the spring thaw became effective and reversed the downward trend. He asks about the speed at which hydro-electric sets can be loaded. This can be quite rapid for, by way of example, it is possible at the Sloy Station where the head is 910 ft (gross) to start and fully load one 32·5 MW set in 5 min. Two sets can be fully loaded in 8 min and all four sets, i.e. 130 MW, in 12–15 min. Undoubtedly, hydraulic conditions can place a limit on the rate at which load can be taken up and make synchronizing difficult, but that is why surge shafts are provided. They usually have sufficient capacity to ensure that full load can be attained in a matter of minutes.

In hydro-electric plant auxiliaries there is usually sufficient storage in the governor air/oil receiver for several full strokes of the guide-vane servo-motor. Assuming that both the normal and standby pumps had failed, this would represent a running time of perhaps 15 min on governor control, and about double this time should the load limiter on the governor be in use. In the earlier stations practically all the standby-governor oil pumps are driven by a small turbine of the Pelton type. In more recent stations a.c. motor-driven pumps have been used because the transmission and distribution systems are now so much more closely interconnected that they are more reliable. The unit auxiliary transformer system is generally adopted for sets above about 7 MW. Standby electricity supplies generally are taken from a station transformer connected to the distribution system, and it has not been the practice to install auxiliary generating plant. Standby lubrication for both the turbine and generator is usually provided by d.c. pumps, so that a station provided with a battery and a water-turbine-driven standby-governor oil pump is capable of coming into service independently of any other auxiliary supplies. Indications and alarms are centralized on the turbine control panel and switchgear control panel. These panels are often arranged in one suite where no control room is provided. Sufficient alarms are provided to give warning of any condition likely to lead to failure, such as low bearing-oil flow, low governor-oil pressure, and high bearing temperature. In 1956, out of the total generating capacity of 808 MW, 660 MW were derived from hydro-electric, 103 MW from steam and the balance of 45 MW from Diesel power.

Mr. Scanes asks what measures are taken to prevent corrosion of reinforcing rods due to percolation of water. Most of the Board's water-retaining structures are of mass concrete, but where they do include steel the only measure taken is to ensure that there is an adequate cover of dense concrete over the rods. It has not been the practice to use any waterproofing materials in any of the concrete used, although care is taken to get a dense concrete on all faces in contact with water, which in the Highlands is usually aggressive. The further safeguard of coating such faces with bituminous paint is also usually taken.

In reply to Mr. Guscott's question about the Amenity Committee, it should be explained that the Act of 1943 made provision for the setting up of this Committee. Its duty is to advise and assist the Board and the Secretary of State in the steps to be taken for the preservation of the beauty of the scenery. This has been applied to transmission schemes as well as hydro-electricity generation works. Transmission and distribution projects have also to be submitted to Planning Committees of Local Authorities and, in the case of National Parks, the Department of Health for Scotland. It is sometimes quite difficult to find suitable routes for overhead lines.

Mr. Warnock's remarks on evaporation losses in hot climates are interesting. In Scotland only about 12–14 in per annum is allowed for evaporation loss, so that in areas of high rainfall the percentage available for power is high. The additional information which he has given about the Ffestiniog pumped-storage scheme is of great value and justifies the claims made in the paper of the suitability of the Highlands for the development of pumped storage. In the North of Scotland there are several sites where the plant would be similar to that at Ffestiniog, and the progress there will be watched with much interest.

Mr. Beverley is correct in estimating that the potential hydro-electric power in the North of Scotland is now about 10^7 MWh. One reason for the increase over the Board's 1944 estimate is that coal costs are rising more rapidly than construction costs, so that it is now possible to consider the development of areas which were not attractive enough previously. Speaking generally, the plant factor adopted for a scheme is that which will give a sufficiently attractive cost of production per kilowatt-hour compared with any other form of generation at the same load factor. The Board's first consideration, of course, is to plan to meet the 38% load factor of the demand in their own area. Surplus from schemes with a lower load factor than this can, however, be exported. While the speeding up of the atomic programme should give the Board the opportunity for disposal of still more low-load-factor power, it is probable that this will now be done by pumped-storage rather than conventional schemes. The sizes of units in the latter category are unlikely, therefore, to increase much, whereas pumped-storage units of 100 MW or greater capacity will be likely.

Mr. Dickinson suggests that economics alone should determine whether pipelines would be used. It has been found, however, that where rock conditions are suitable, the use of tunnels instead of steel pipelines does not result in a more expensive scheme. In addition, there may be incidental advantages, e.g. savings in such scarce materials as steel plate and cement. The substitution of a tunnel for a surface pipeline may not necessarily involve an underground station in Scotland, but nothing approaching the saving of 30% quoted by Mr. Dickinson for an underground station has been found. The actual difference has generally been small even where the most favourable rock conditions are found.

Mr. Picken is correct in stating that the energy processed in any large pumped-storage schemes developed in the North of Scotland might have to come from as far afield as South Lancashire and be returned there. D.c. transmission is a possibility if large schemes are developed, but at present prices underground cables would be too costly.

In answer to Mr. Witter, the Board have not deemed it necessary to place a limit on the life of their reservoirs, on the ground that experience with them should be little different from what has apparently happened over several centuries in the case of the natural lochs in Scotland.

DISCUSSION ON

'CONDUCTION AND INDUCTION PUMPS FOR LIQUID METALS'*

NORTH-EASTERN CENTRE AT NEWCASTLE UPON TYNE, 10TH DECEMBER, 1956

Mr. N. C. Adcock: The author gives the three most important liquid metals as sodium, sodium-potassium and bismuth, and indicates that the linear induction pump seems to be the most favourable where large quantities of sodium and sodium-potassium are to be pumped. For liquid-fuel reactors, however, where, say, a bismuth-uranium fuel is used, the linear induction pump is not so favourable, owing largely to the higher resistivity and density of this metal. The author's analysis of the various types of pump indicates that for pumping bismuth the d.c. conduction pump has many advantages. Reference to Table 3, however, shows that large pumps of this type require currents up to 200 kA. To provide this current a rectifier or homopolar generator would be needed, and because of this very high rating, would have to be mounted close to the pump. Since in a liquid-fuel reactor the bismuth will be highly radioactive, difficulties may be experienced in removing the pump from the tube without disturbing the tube circuit, and also in the maintenance of the pump and the rectifier or homopolar generator set.

The advantages of low-level insulation are mentioned, but it is possible that with most types of pump the thermal limitations of insulation will prove more important. Here again the d.c. conduction pump shows to advantage, since the excitation coils for the magnetic field can be well removed from the heat source. Table 3 also compares the d.c. conduction pump and an Alip having a flow rate of 10 000 gal/min when pumping sodium. The overall efficiencies are similar, but the latter is 8–9 times smaller. Will the author give the corresponding comparison for bismuth pumps?

It is stated that the windings of the Alip can be split to facilitate the removal of the cores from the tube. With a split-winding Alip, however, all the advantages of the pancake form of coil and the associated coil grading would be lost, since a double-layer winding would be necessary. There would also be a loss of pump thrust, owing to a reduction in circumferential channel area in contact with the stator cores, this space now being occupied by the stator-winding overhangs.

The author's reference to the side-electrodes used in Flip and to their increasing the losses compared with the Alip is, of course, true, but it should be appreciated that the low-resistivity copper side-electrodes can be so proportioned that the additional loss compared with the tube and liquid losses are almost negligible. Similarly, the magnetic circuits of most types of pump are also designed so that the iron losses are reduced to an absolute minimum. This is illustrated in Section 2.6, where the losses of an experimental Alip are analysed. The tube-wall loss in this analysis is extremely low, because a thin wall is used. Since the wall thickness is a major parameter in pump design, an indication of the effect on the pump design and performance given in Tables 1 and 2 by increases in the tube-wall thickness would be of interest.

Mr. T. W. Berrie: The importance of liquid-metal pumps is out of all proportion to their physical size, for there is no doubt that the reactors used in future atomic power stations will be of the enriched-fuel fast thermal type. The most effective way to handle the high rate of heat transfer to the cooling medium is by using liquid metals, and a thoroughly reliable pump is therefore essential. Furthermore, the pumping of liquid metals and slurries containing liquid metals is becoming of increasing importance in other types of industry.

I should like the author to convince me that the electromagnetic pump is a serious rival to the conventional submersible mechanical pump, in view of the high efficiency and power factor of the latter. Has he had any experience of the two types, carrying out identical functions, so that comparative performances can be fairly judged?

With regard to the d.c. conduction pump, are there any adverse effects produced by the large currents flowing in the pipework and associated metalwork near the pump?

Can the performance and efficiency of induction pumps be increased by increasing the number of phases used, or is any advantage outweighed by increased costs?

On the grading of the windings of induction pumps the alternatives are either no grading, thus giving the maximum power output, or grading the whole winding, which may not be much more complicated than grading the end turns. What proportion of the whole winding is classified as 'end turns' in practice?

Finally, in view of the cost and complications introduced in some pumps by introducing facilities for removal of the pump without disturbing the pipework, and also the small amount of maintenance which is normally required on the windings, is it necessary to introduce this feature into the design?

Dr. L. R. Blake (*in reply*): In reply to Mr. Adcock, the linear induction pump has such a low efficiency and power factor with bismuth that its use is virtually ruled out and no effective comparison can be made between it and the d.c. conduction pump, as with sodium. Incidentally, the 8 300 gal/min d.c. pump in Table 3 should not be regarded as typical: its size could be reduced to that of the 8 300 gal/min Alip, and the 8–9 times difference in size refers to the d.c. pump and its homopolar generator, compared to the Alip without auxiliaries. If the tube-wall thickness of the Alip discussed in Section 2.6 were increased to 0·064 in, the efficiency would fall from 41 to 37% with sodium and from 36 to 32% with sodium-potassium.

In reply to Mr. Berrie, I have no direct experience of mechanical and electromagnetic pumps of identical ratings, but suggest that the great virtue of the linear induction type of sodium pump is its reliability and freedom from routine maintenance. If a good high-temperature electrical insulation can be developed to avoid the necessity for thermal insulation between the duct and the winding, forced cooling can be avoided, the size of the pump can be reduced and the power factor need not fall below 0·6 in large pumps. Since the pumping power is small in comparison with the reactor power output, the lower efficiency in comparison with the mechanical pump does not cause concern.

All electromagnetic pumps, including the d.c. pump, have large currents flowing in the pipework, but there is no evidence that this produces any adverse effects. The performance of the linear induction pump can be improved slightly by doubling the number of phases, but not enough to justify the special trans-

* Blake, L. R.: Paper No. 2111 U, July, 1956 (see 103 A, p. 49).

former required, except in exceptional circumstances when it is desired to operate at high gap flux densities and tooth saturation is limiting. Normally, grading of the winding is carried out over the end poles or pole pairs, say 12–24 coils out of 48–96. Grading the whole winding is not the optimum arrangement in a practical pump, and it also complicates construction and design. It is desirable to be able to remove the winding without disturbing the duct, since it is believed that the life of the duct is well in excess of the winding under reactor conditions, and cutting out the duct is normally to be avoided.

DISCUSSION ON 'POWER-SYSTEM ENGINEERING PROBLEMS WITH REFERENCE TO THE USE OF DIGITAL COMPUTERS'*

NORTH STAFFORDSHIRE SUB-CENTRE, AT HANLEY, 10TH JANUARY, 1957

Mr. H. A. P. Caddell: Investigations into the load curves of individual appliances, as described in Section 5.1, are useful but they are difficult to 'mount', and because they are necessarily small, it is difficult to be satisfied as to how far they can be taken as typical. We require a method of analysis based on the accounting figures and load readings that are taken as routine, so that a constant watch can be kept on load-curve changes and development. Consequently the method described at the beginning of the Section is interesting.

Whether the basic assumption that the class load groups have the same shape for all the substations on any particular day is true or nearly true will depend on the load content of each class group. For the industrial load it is very probable that there are differences between the groups in the incidence of single- and three-shift factories which will make the load curves different. We know that the load contents of the domestic load vary considerably. For Sub-Areas—usually 100 000–200 000 consumers—cooker saturation varies from about 10 to 35%, and for Districts—usually about 25 000 consumers—the saturation varies from about 10 to 55%. There are similar variations for other appliances, of which heating is an important item.

We could get over this difficulty be selecting only substations which have similar load contents. Another possible method would be to arrange the substation equations to have more components corresponding to the loads which we could feel satisfied have similar curves. About eight components would probably be sufficient to cover all three major classes of consumer. It would also be necessary to make another regression analysis to obtain the consumptions of these components.

On practical considerations, the routine figure of consumer class consumptions for Sub-Areas and Districts do not correspond to Grid point networks. For Sub-Areas, however, there is good correspondence between the two, and network changes do not often occur. For some Districts there is quite good correspondence, but network changes are more frequent.

It may be difficult to make adjustments in respect of continuous meter reading, and the weather too has an effect on this. One solution would be to take the annual consumption because the overlap is less. I suspect that accuracy would be lost in so doing, because the ratio of summer to winter consumption differs for the classes of consumers. Thus, the summer to winter ratio for domestic consumers is about 60%, for commercial consumers about 50% and for industrial consumers about 80%. For consumers on these continuous cycles it would be possible to produce figures of daily kWh read, and there may be statistical means by which this could be used to give more accurate class consumption figures.

Messrs. C. Robinson and **D. H. Tompsett** (*in reply*): We wished to include in the paper some reference to computational work which might be of interest to distribution engineers, in addition to the examples of transmission-system operational and engineering problems. Section 5 therefore outlines the application of regression analysis to consumers' load curves. In this country, the principal investigations of this type have been carried out by the Utilization Research Section of the Central Electricity Authority.

A point of interest brought out in Section 5.1 is that the necessary arithmetical operations can be expressed in matrix form, which means that they are well suited to high-speed digital computation on a universal-type machine such as Deuce.

Mr. Caddell mentions several points which are of interest as representing the practical problems facing distribution authorities. We feel that his proposal to increase to eight the number of characteristic components can be used to account for many of the differences in both factory shift-working and appliance saturation.

A balance must clearly be struck between (i) the number of consumer classes, (ii) the labour of establishing individual class consumptions, and (iii) the number of total load curves available for analysis. With regard to item (ii), an important point is the degree of correspondence between Grid-point networks and accounting boundaries. It is unfortunate if data available at each of a number of Grid points can be used only as a single total figure, which is presumably necessary if a Sub-Area basis must be used for the class consumptions.

The variations between individual consumers will naturally limit the subdivision possible under item (i). Provided that the resulting groups are sufficiently large for the aggregate behaviour to be uniform, these variations present no difficulty. Further work on the subject may show that statistical methods can be employed in establishing class consumptions, as Mr. Caddell suggests. We are convinced that high-speed digital computers will assume increasing importance for all such investigations.

* ROBINSON, C., and TOMPSETT, D. H.: Paper No. 2121 M, September, 1956 (see 103 B, Supplement No. 1, p. 26).

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, AUGUST 1957

CONTENTS

Bibliographical References.—It is requested that bibliographical reference to an Institution paper should always include the serial number of the paper and the month and year of publication, which will be found at the top right-hand corner of the first page of the paper. This informati-n should precede the reference to the Volume and Part.

Example.—SMITH, J.: 'Overhead Transmissions Systems', *Proceedings I.E.E.*, Paper No. 3001 S, December, 1954 (102 A, p. 1234).

Published by The Institution, Savoy Place, London, W.C.2. *Telephone:* Temple Bar 7676. *Telegrams:* 'Voltampere, Phone, London.'
Printed by Unwin Brothers Limited, Woking and London.